
PETM, ANCIENT HELL ON EARTH
FEATURING:
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EP. 035 - 28/04/2017
DEN OF LORE
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PROFESSOR & RESEARCHER

Level 1: Simple observations and the PETM
Level 2: A primer on global carbon cycling
Level 3: A background on Cenozoic climate
Level 4: The basics of carbon cycling during the PETM
Level 5: Possible ideas for carbon injection
Level 6: Testing climate model ideas across the PETM
Level 7: Problems with PETM records
Level 8: Other Paleogene hyperthermal events
Level 9: Rethinking the global carbon cycle
Level 10: Emerging Scientific Issues

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ALICE'S

ADVENTURES IN WONDERLAND.

BY

LEWIS CARROLL.

WITH FORTY-TWO ILLUSTRATIONS

BY

JOHN TENNIEL.

London

MACMILLAN AND CO.

1865.

Jerry's

~~ALICE'S~~

ADVENTURES IN WONDERLAND.

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Houston

Rice University

~~London~~

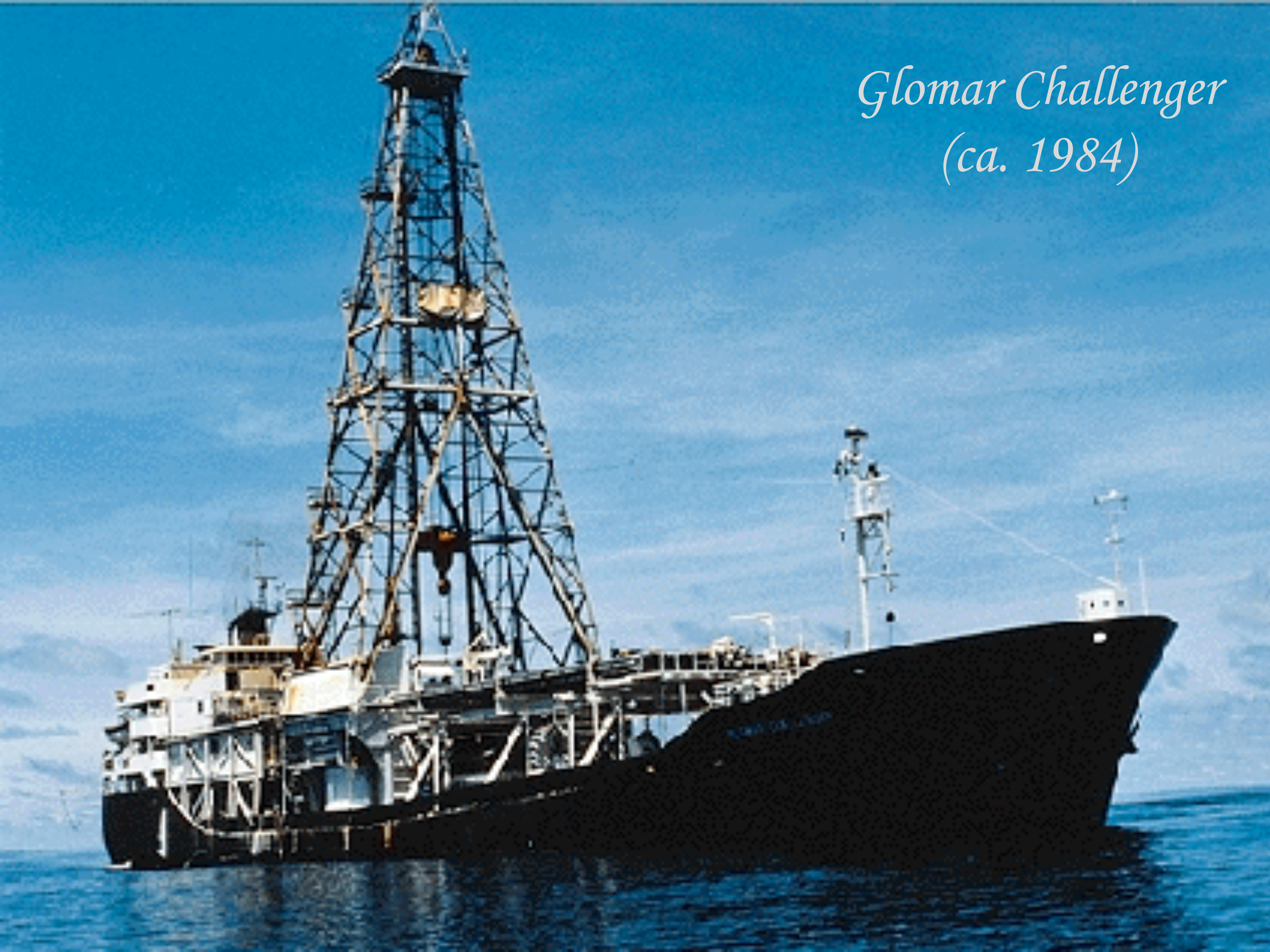
~~MACMILLAN AND CO.~~

~~1865.~~

2015

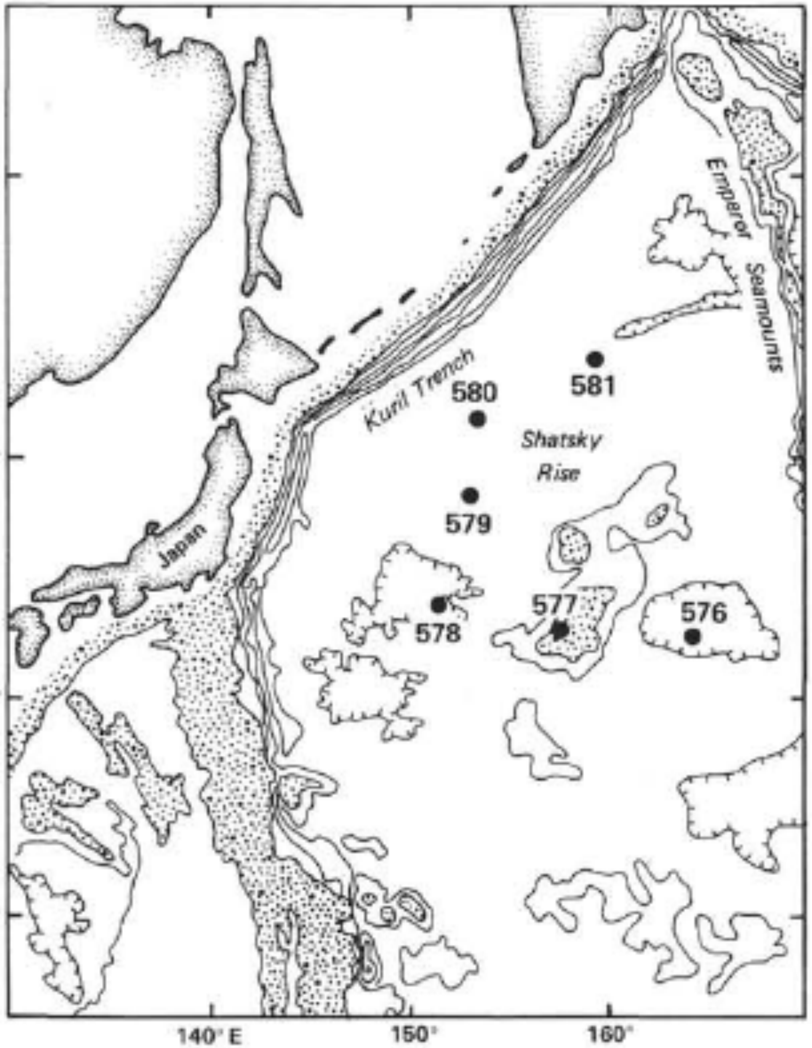
Figure 1. Colleagues inspecting a freshly baked idea

2. Down the Rabbit Hole



Glomar Challenger
(ca. 1984)

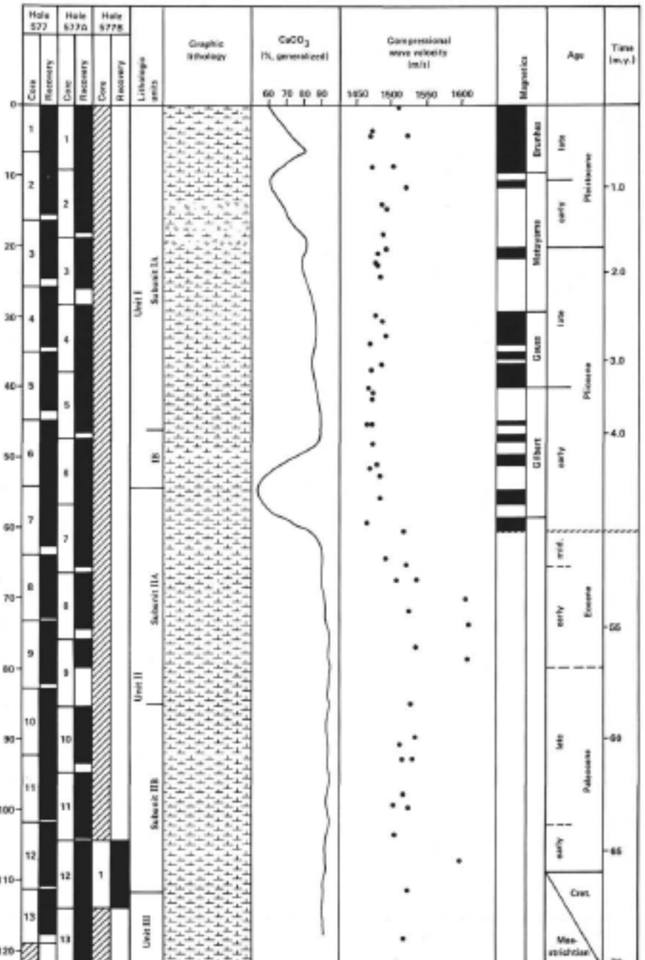
DSDP Leg 86, Hole 577



0

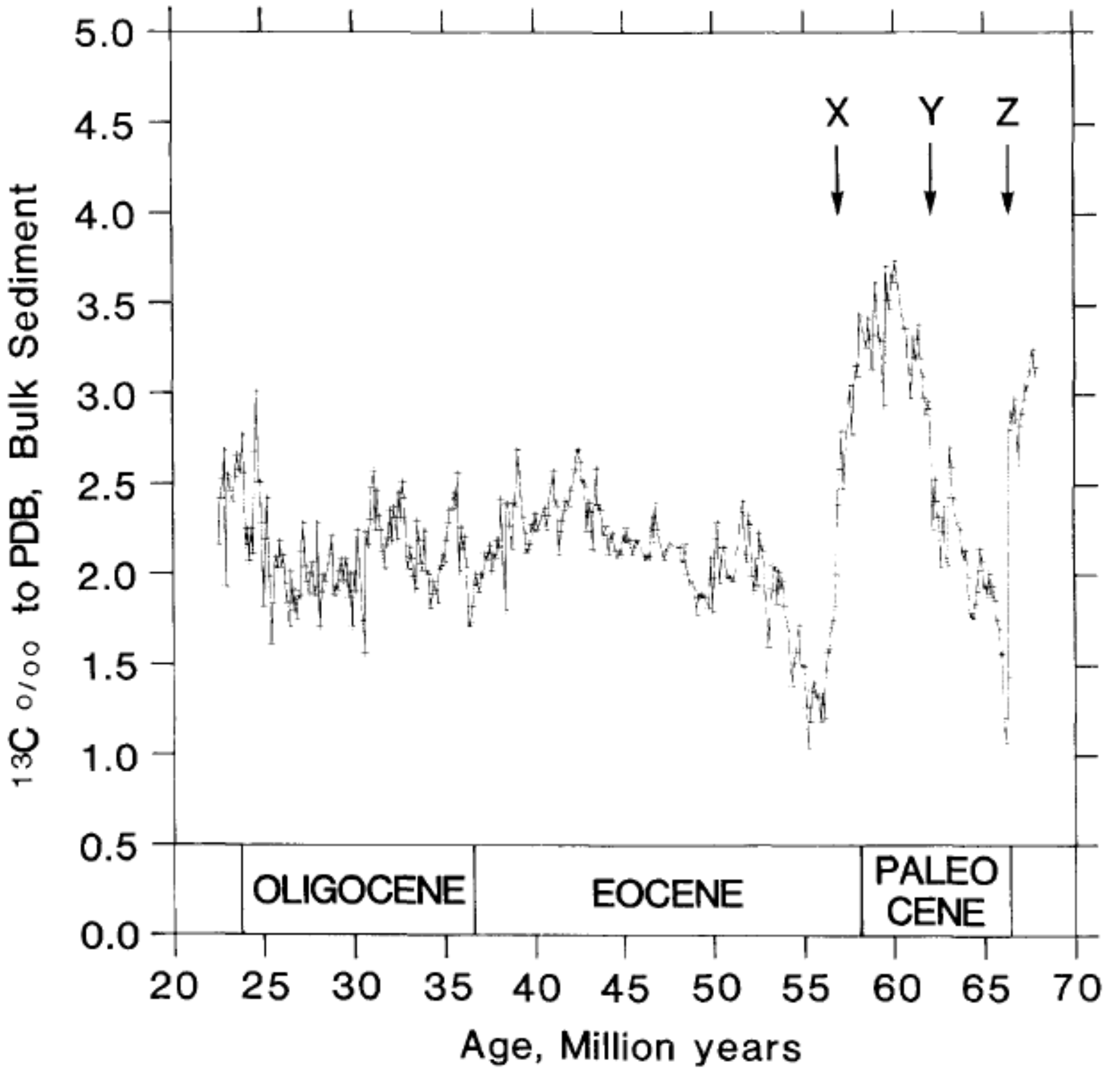
Depth (m)

120



Shipboard Scientific Party, 1984

(Long-term) Paleogene Bulk Sediment $\delta^{13}C$ Stratigraphy

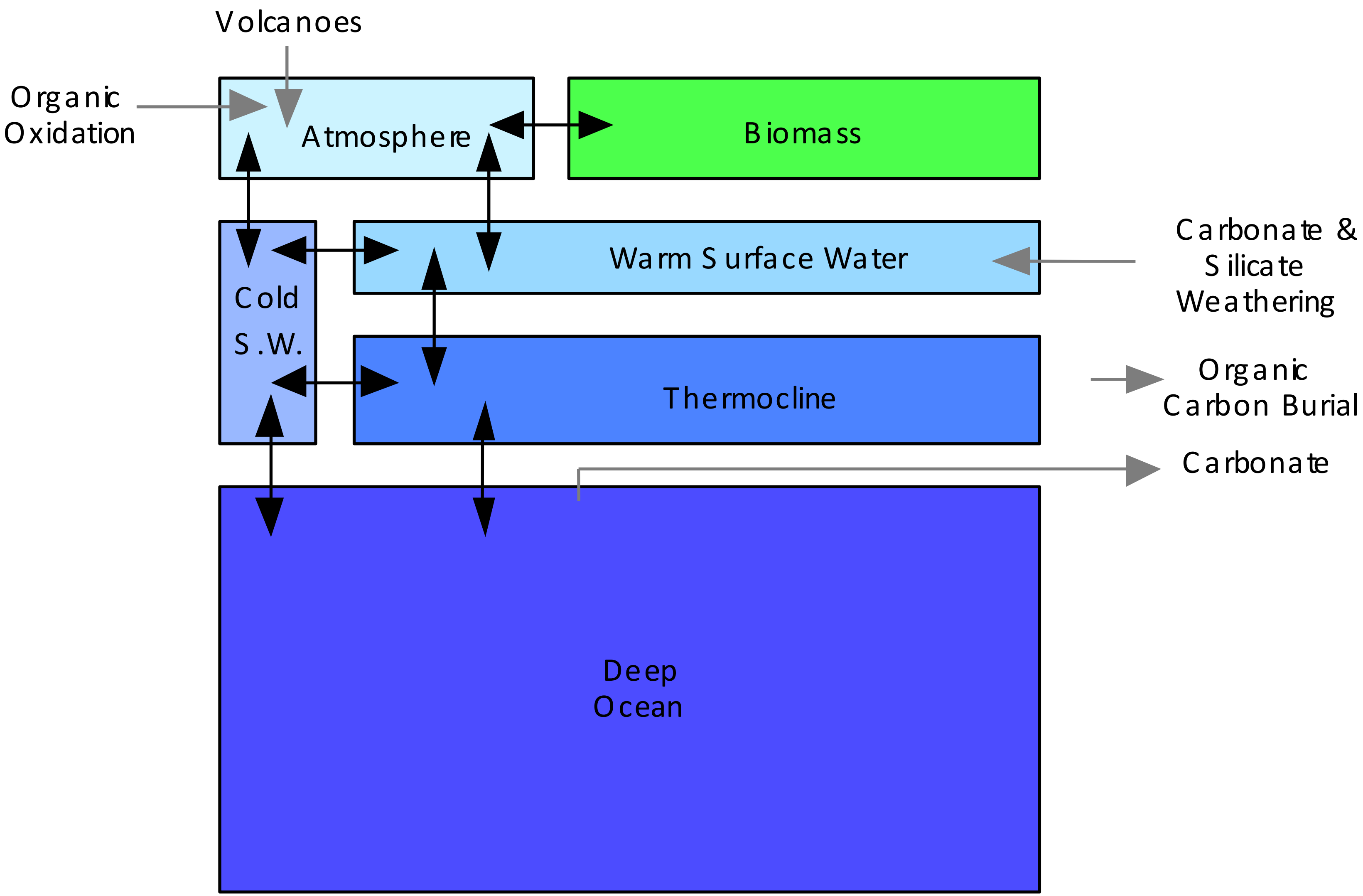


Key points:

- Bulk sediment $\delta^{13}C$ records correlate across multiple sites
- Major oscillations in $\delta^{13}C$ occur
- Must relate to inputs and outputs of organic C to the ocean-atmosphere

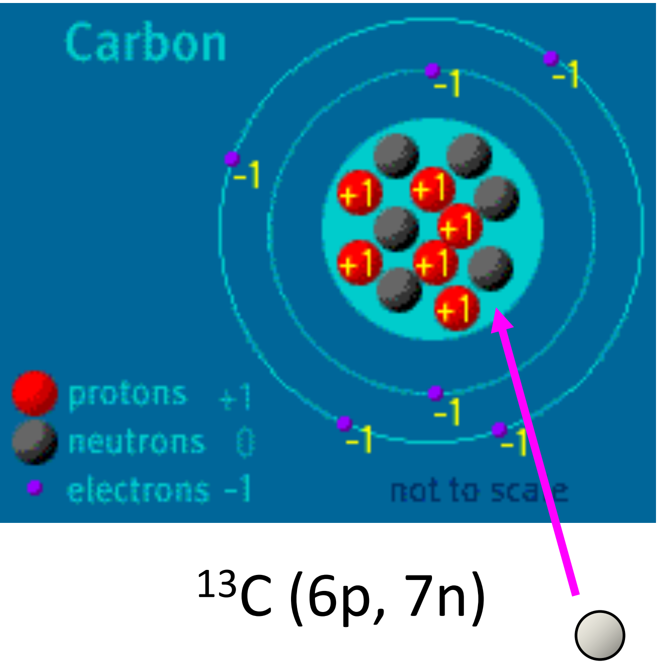
[*Shackleton, P³, 1986*]

Level 2: 1. What is the exogenic carbon cycle?



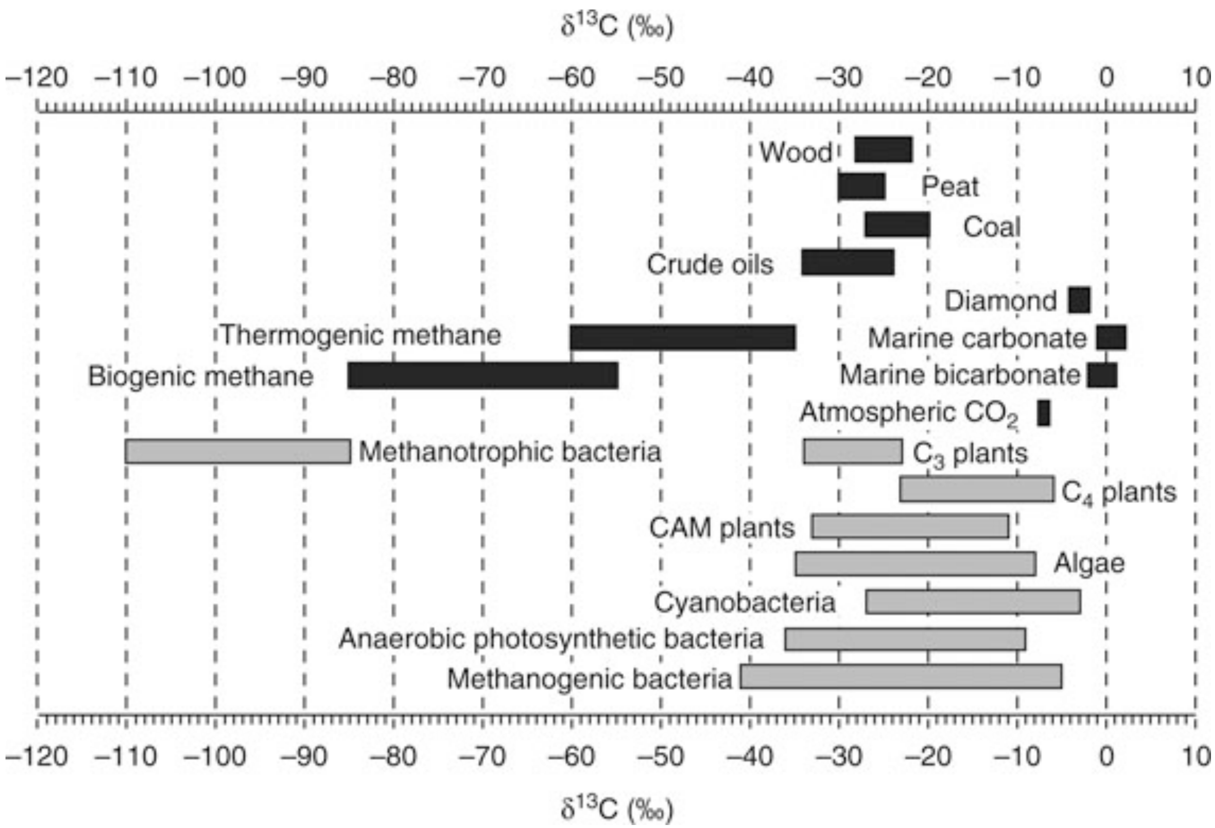
- Carbon in the ocean, atmosphere and biosphere
- About 40,000 Gigatons total. Most in the deep ocean.

Level 2: 4. What are stable carbon isotopes?

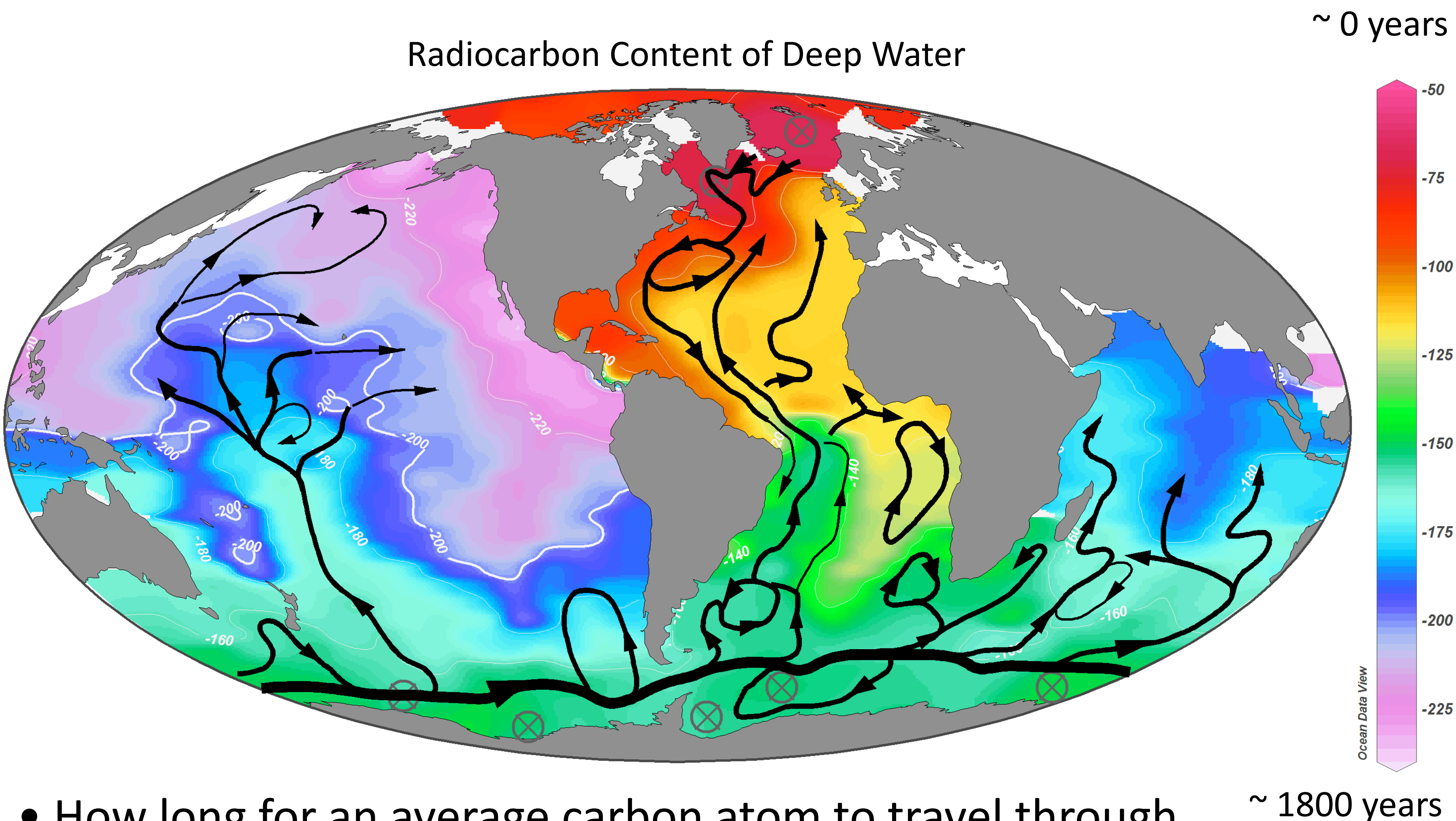


^{13}C (6p, 7n)

- Two stable isotopes ^{13}C, ^{12}C
- Fractionation leads to different ratios
- $\delta^{13}C \sim {}^{13}C/{}^{12}C$

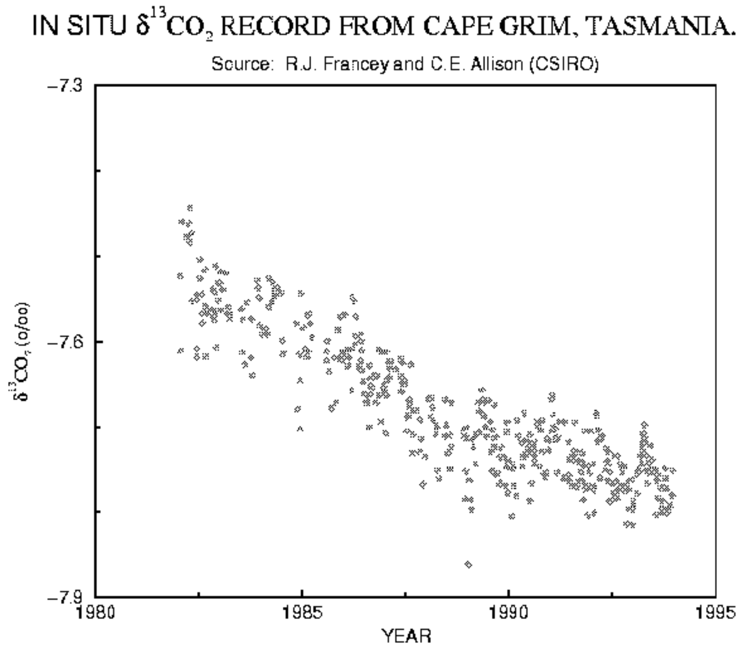


Level 2: 2. What is the cycling time?

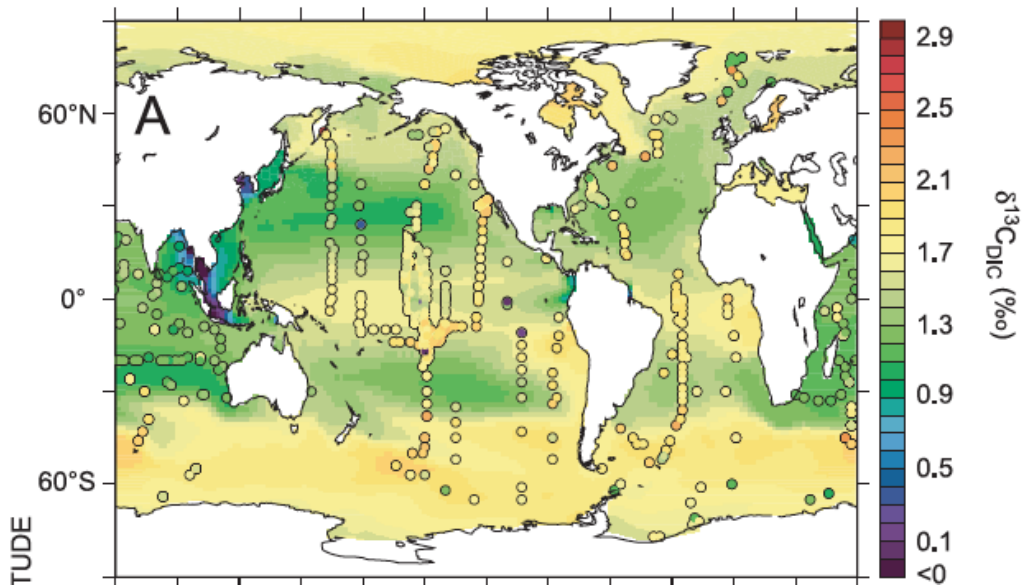


- How long for an average carbon atom to travel through exogenic carbon reservoirs. On the order of 100 years.
- Massive deep ocean the slow

Level 2: 5. How do stable carbon isotopes help track flow?



δ^{13}C of surface water DIC

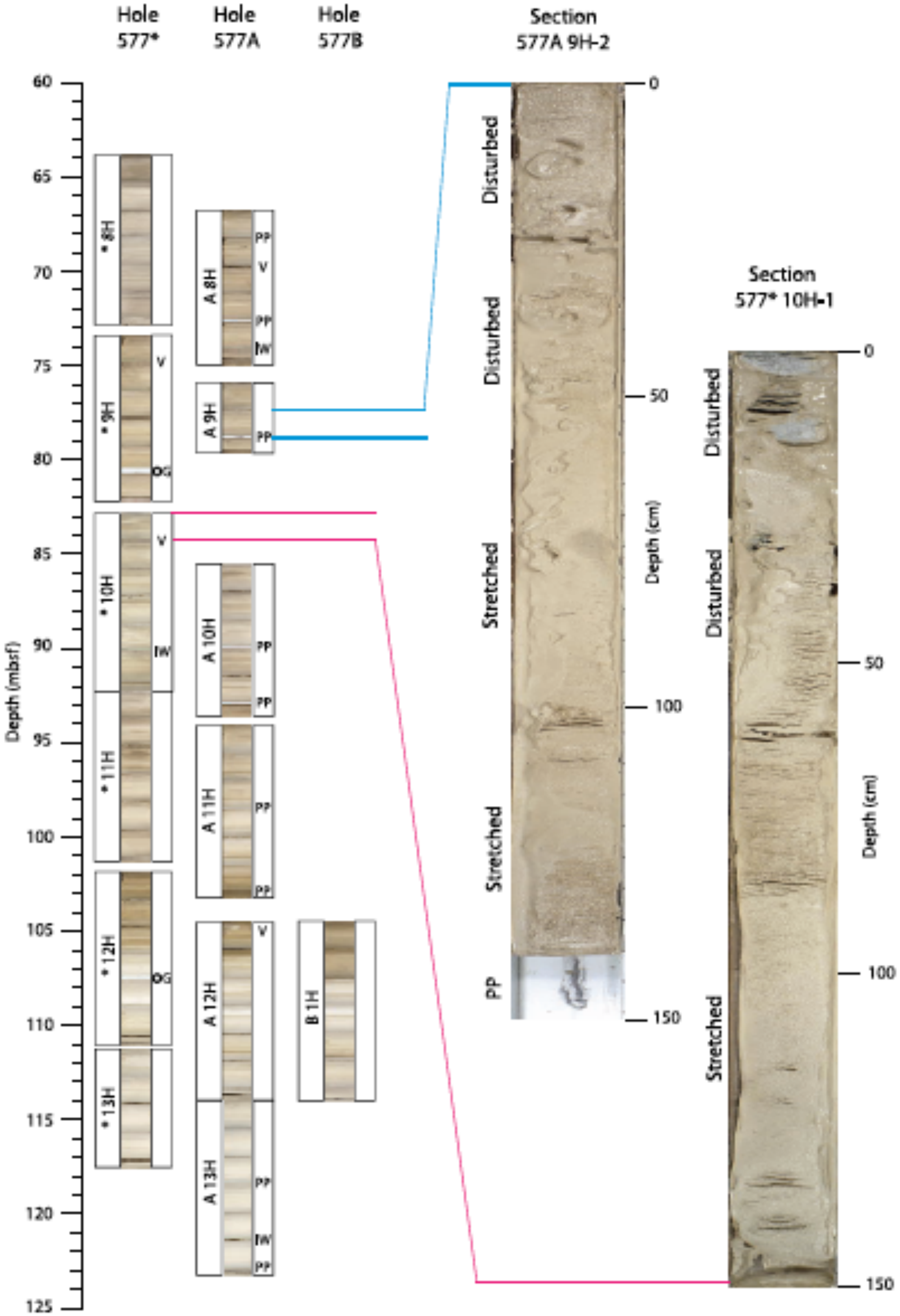


[Tagliabue and Bopp. 2008]

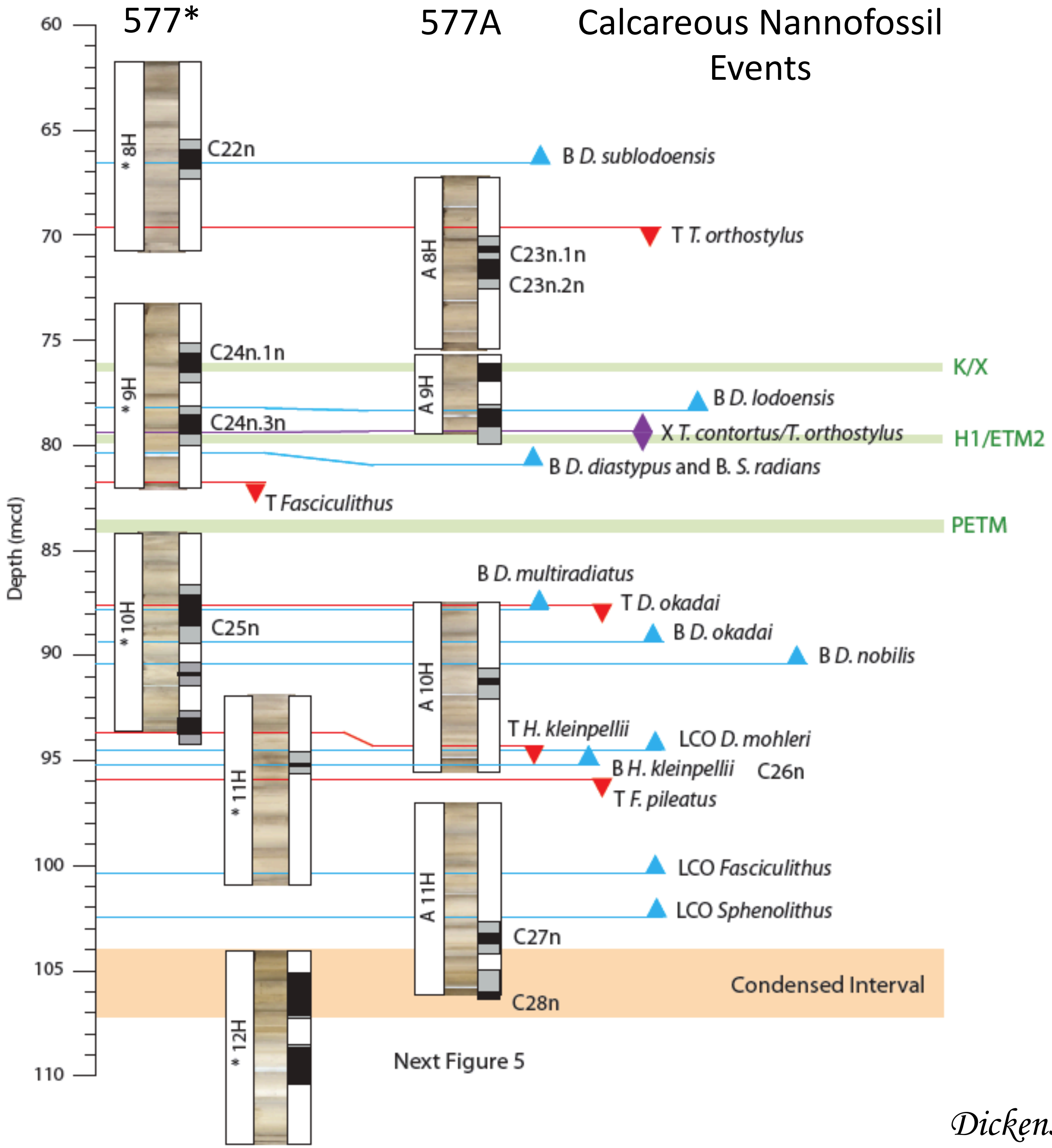
3. Finding the door behind the curtain

Time/Depth issue with cores

Example: Site 577



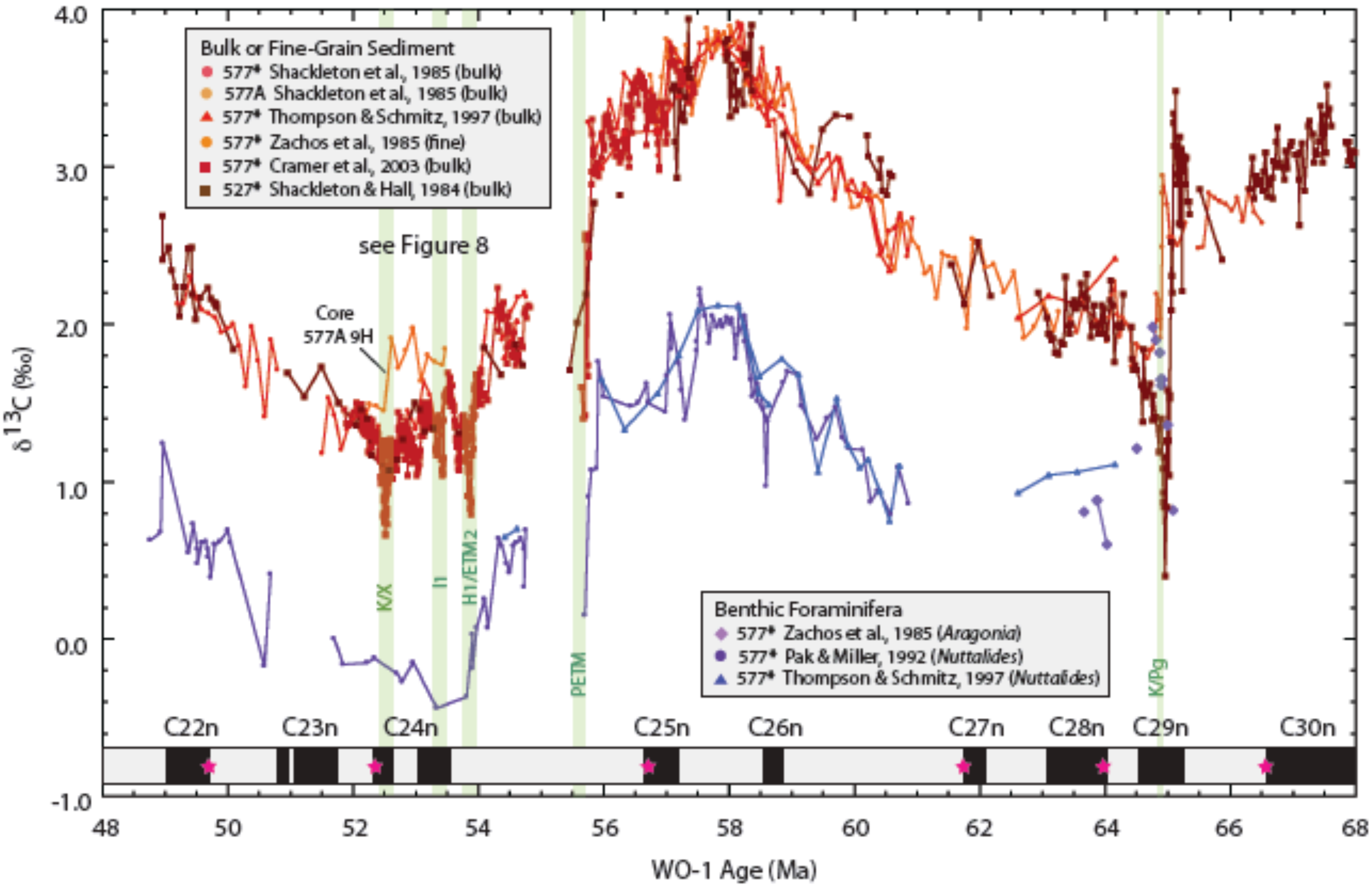
[*Dickens and Backman*, *News. Strat.*, 2013]



Lower Paleogene Interval at DSDP Site 577

Dickens & Backman, News. Strat., 2013

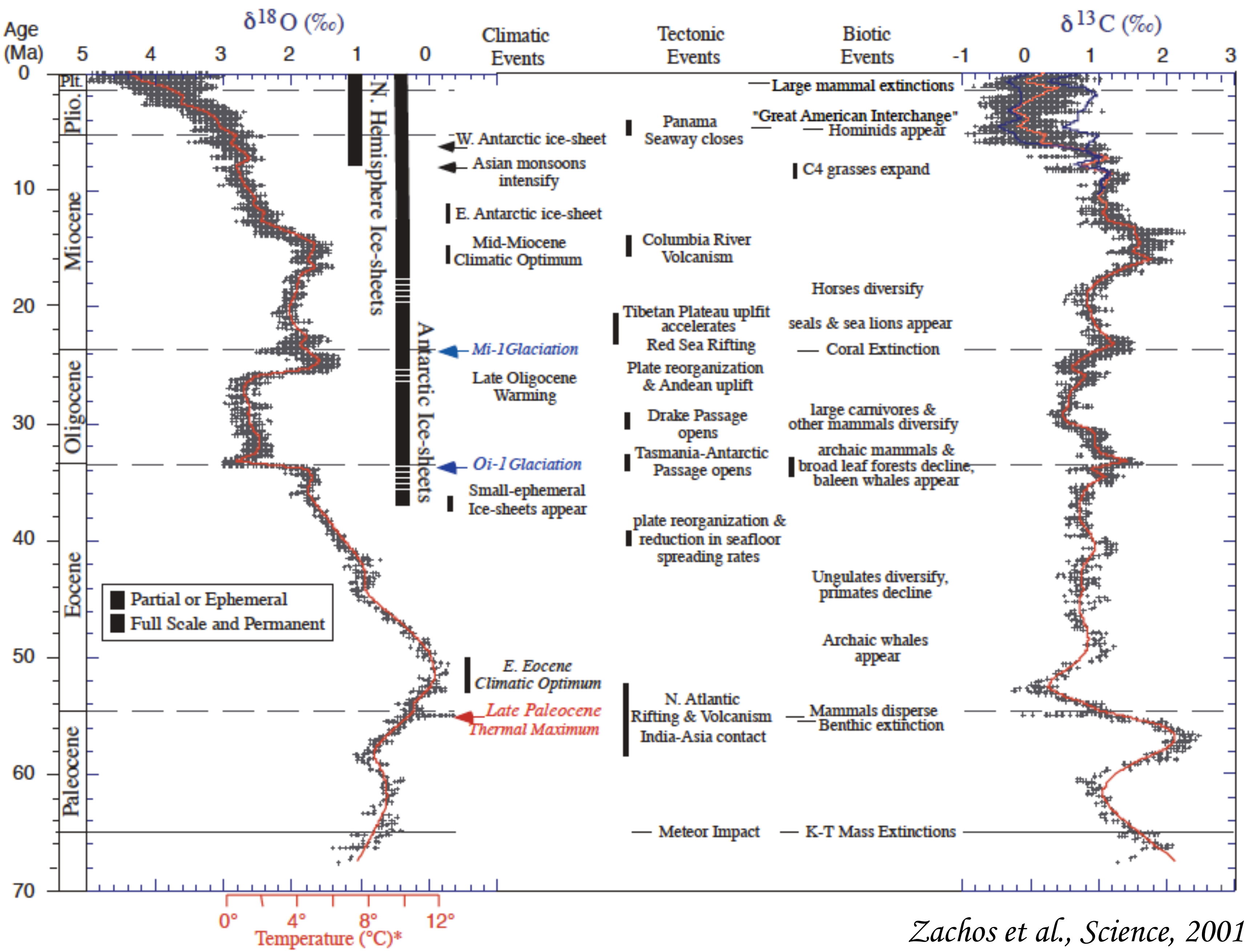
Carbon Isotope Records at DSDP Site 577



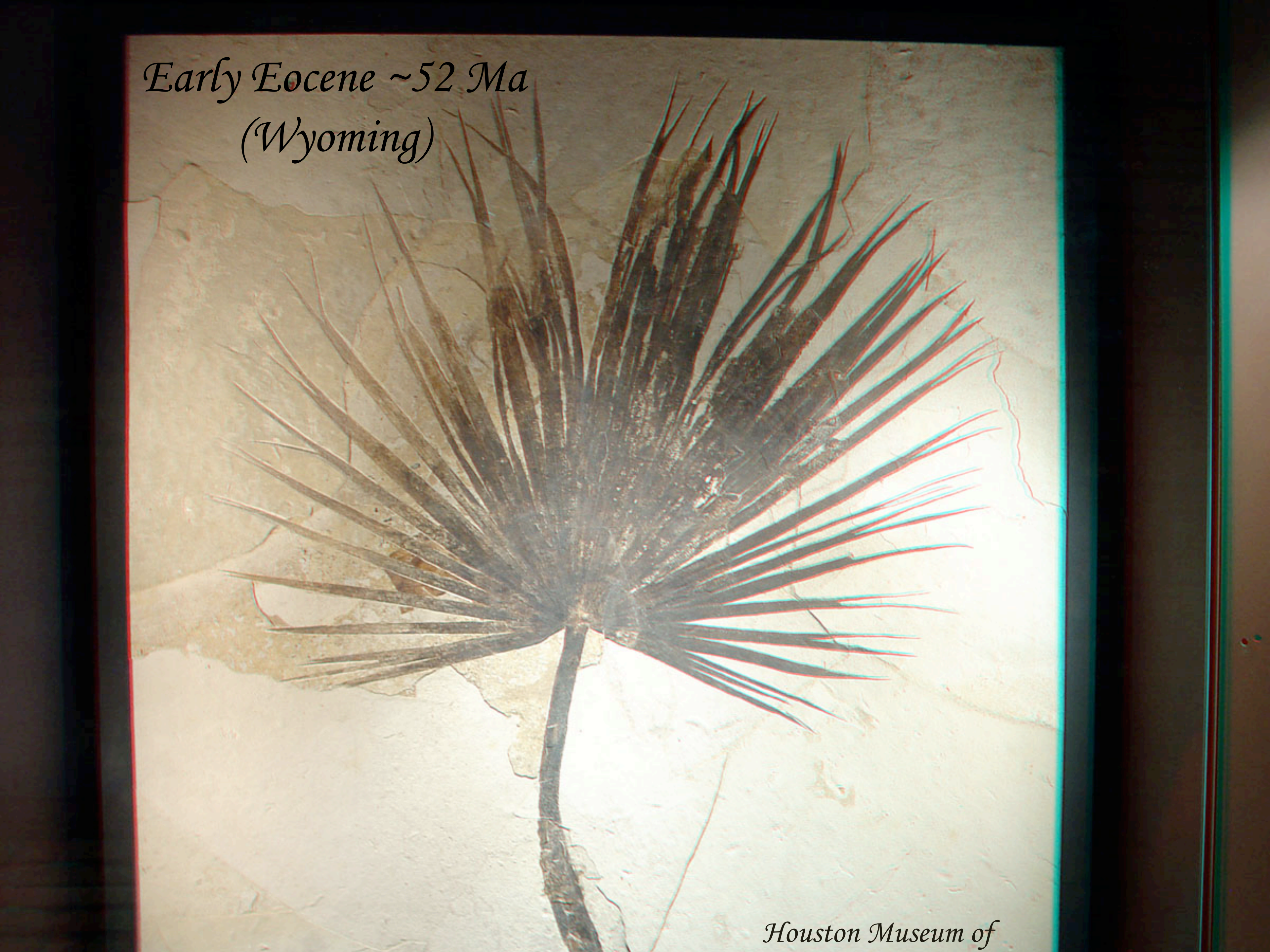
Dickens & Backman, News. Strat., 2013

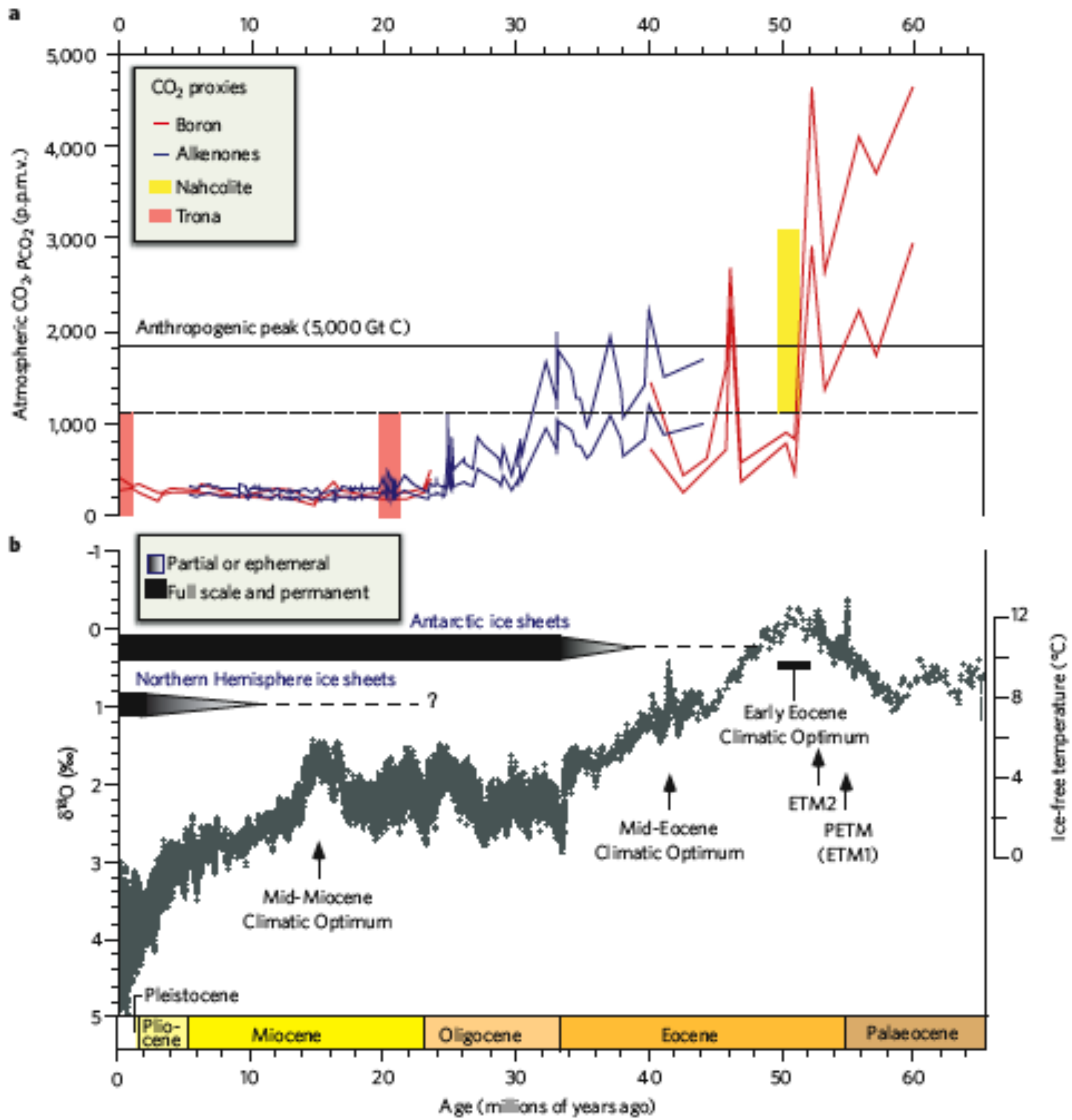
4. *"Drink me"*

Cenozoic Benthic Foraminifera Stable Isotope Compilations



Zachos et al., Science, 2001

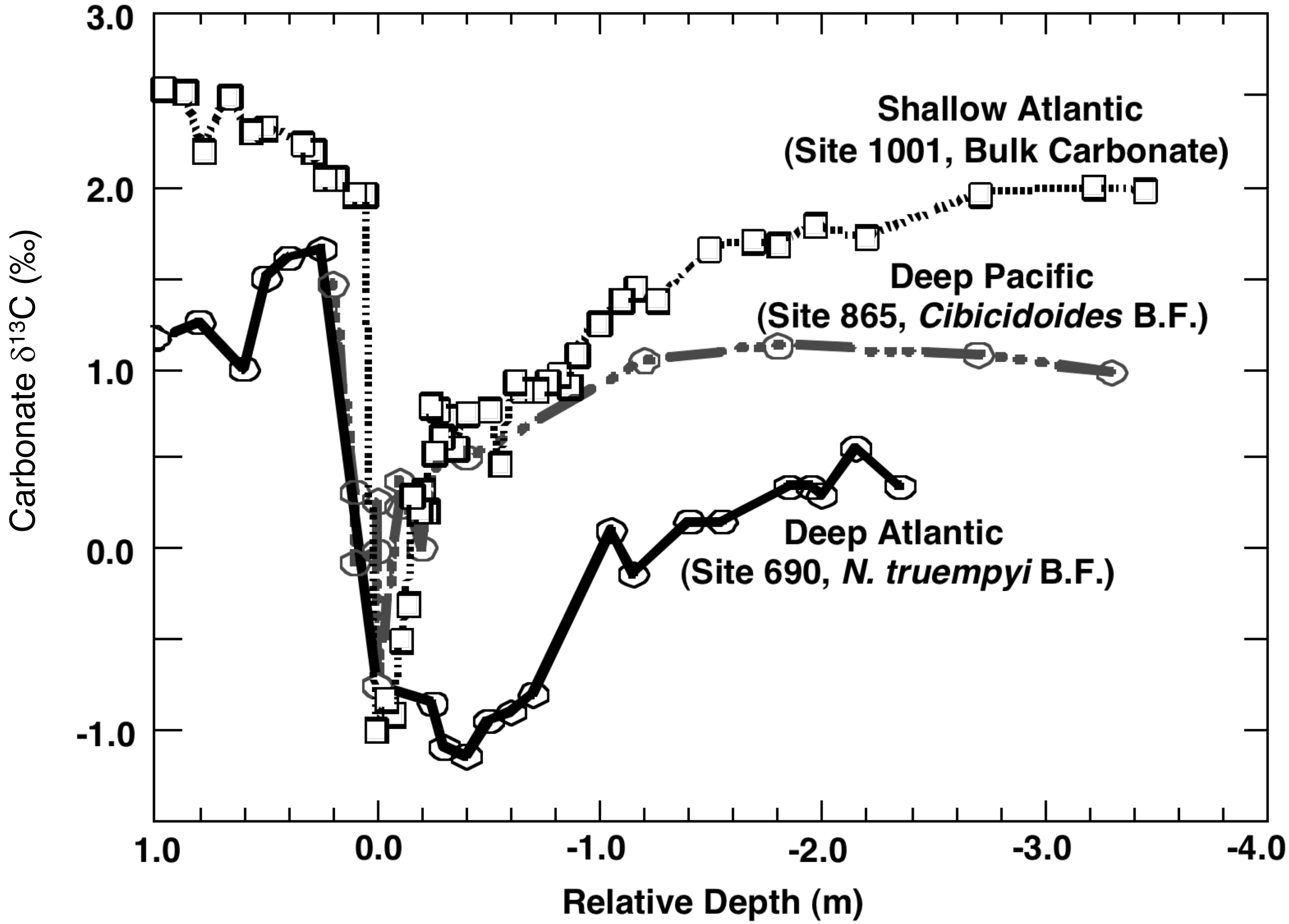

Early Eocene ~52 Ma
(Wyoming)
Houston Museum of



Zachos et al., Nature, 2008

5. Things stretched very tall

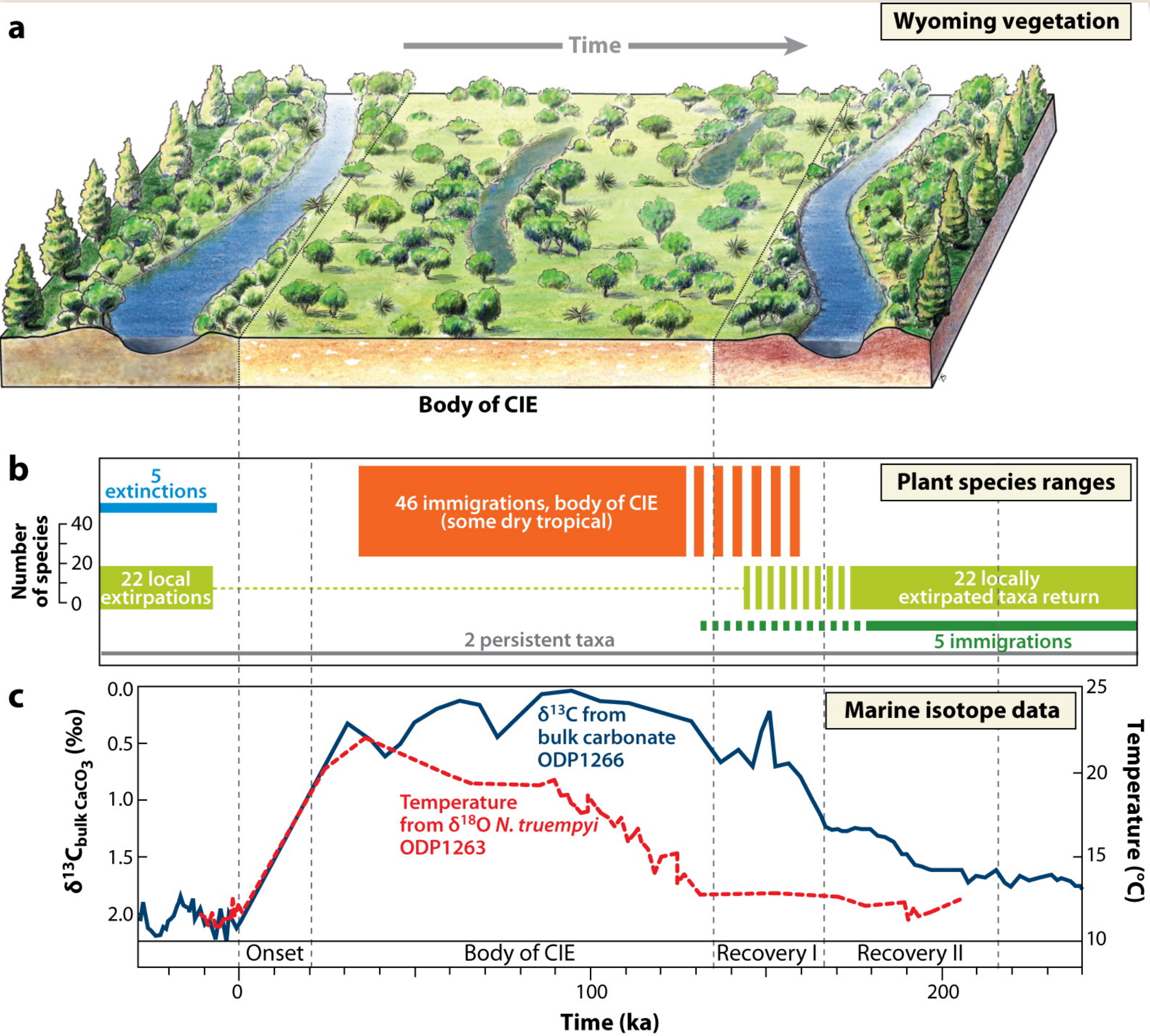
Some "early" PETM d13C Records



Sources: Kennett & Stott, Nature., 1991

Bralower et al., Paleoceanography, 1995; Geology, 1997

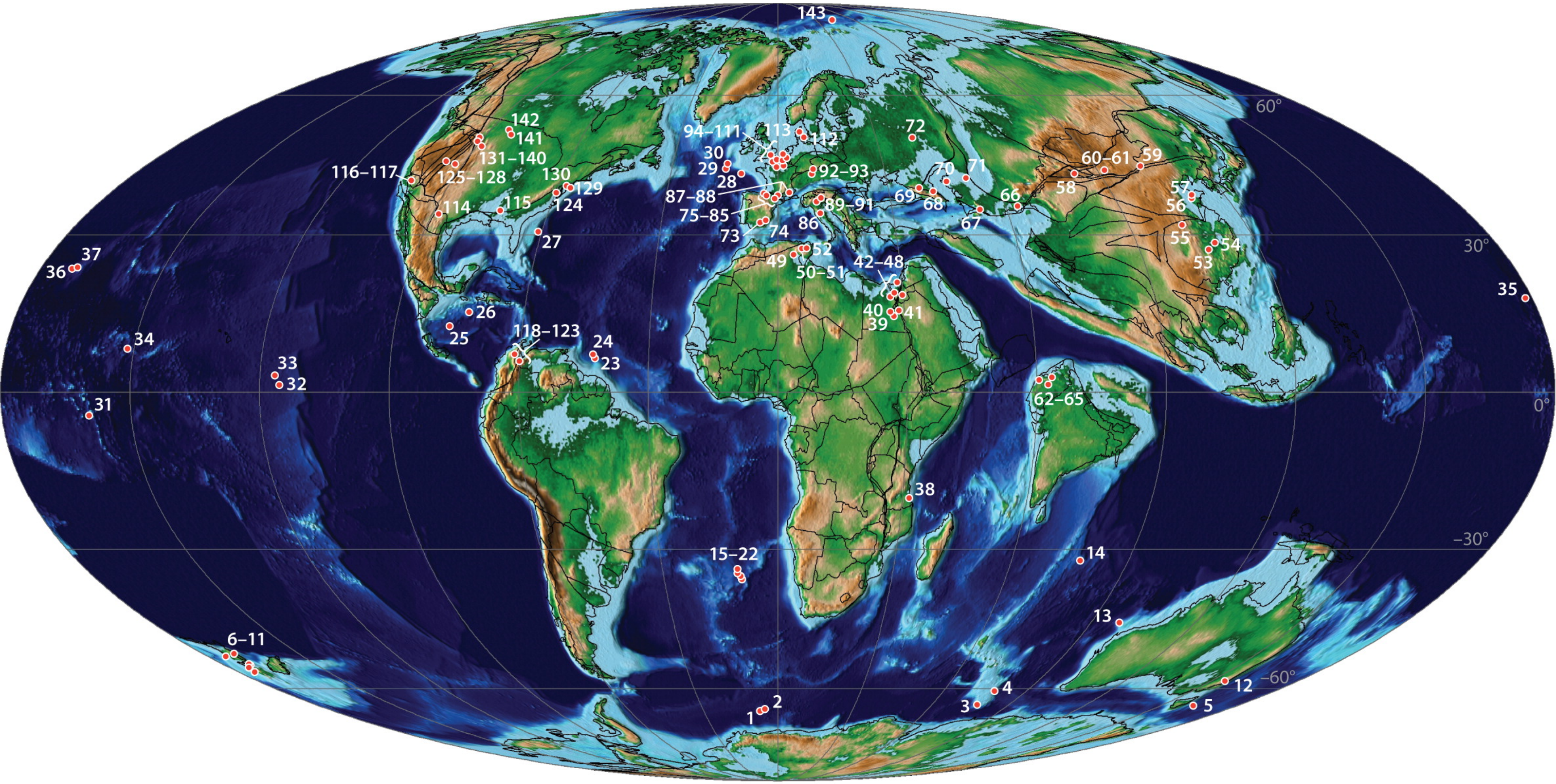
Level 1: 3. What is the PETM?



- Extreme warming
- Changes in fossils
- Changes in carbon cycling
- Changes in vegetation

McInerney FA, Wing SL. 2011.
Annu. Rev. Earth Planet. Sci. 39:489–516

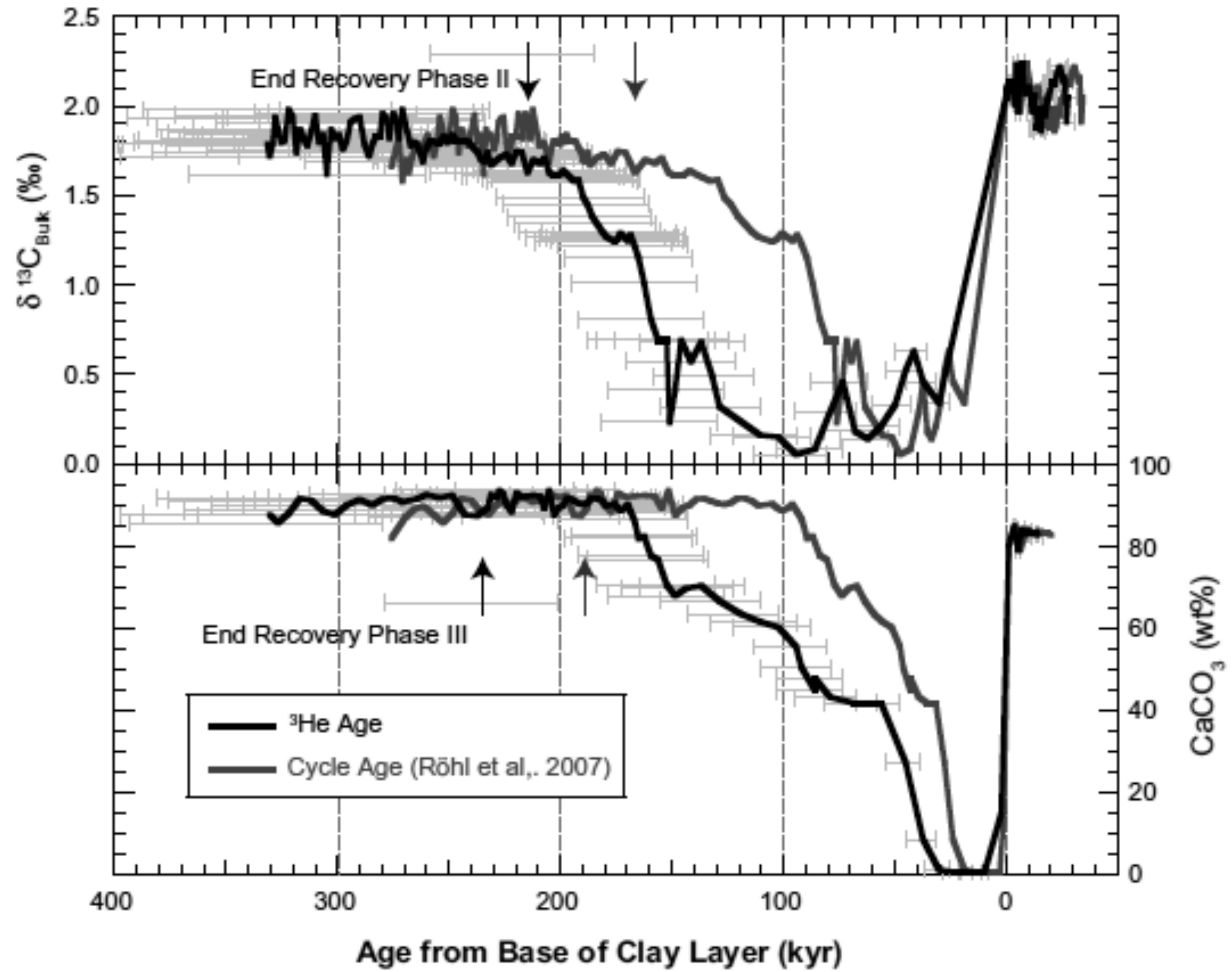
Level 1: 4. Where has the PETM been found?



McInerney FA, Wing SL. 2011.
Annu. Rev. Earth Planet. Sci. 39:489–516

- >200 locations circa 2017
- Land and ocean sites

Timing of the PETM $d^{13}C$ Excursion

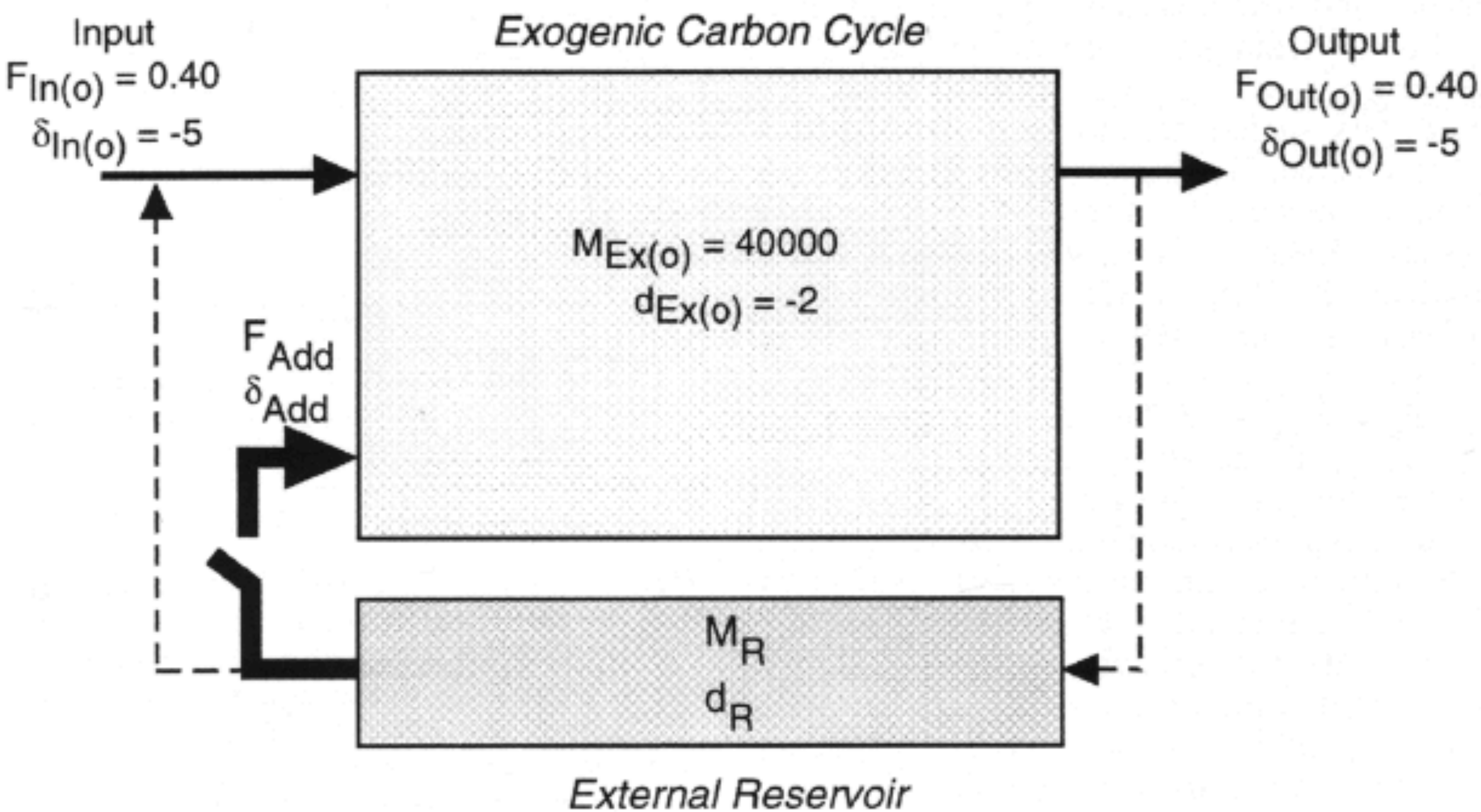


Murphy et al., GCA, 2010

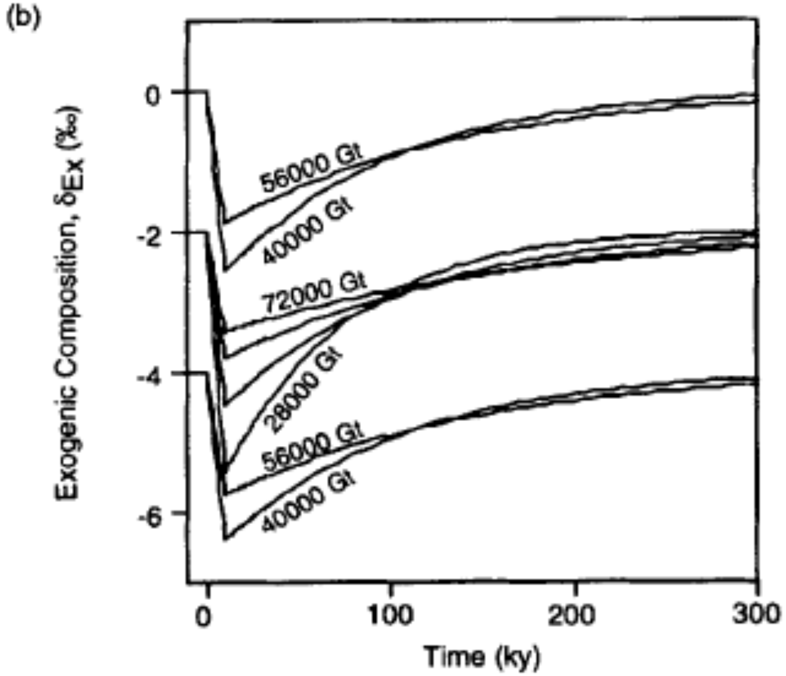
6. A Mass Balance Problem

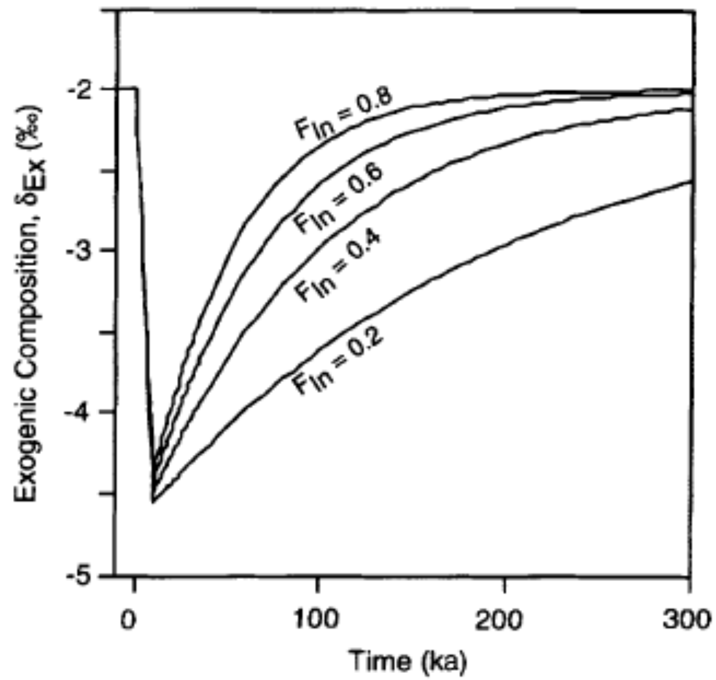
A Simple Model for a Global Carbon Isotope Excursion

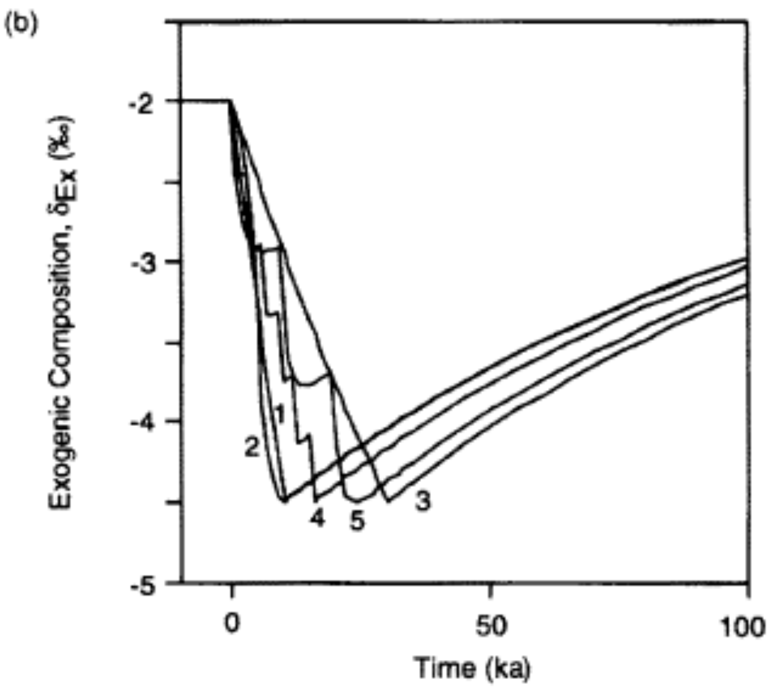
Masses in Gigatonnes; Fluxes in Gt/yr; Delta in per mil



Dickens, Geol. Soc. London, 2001



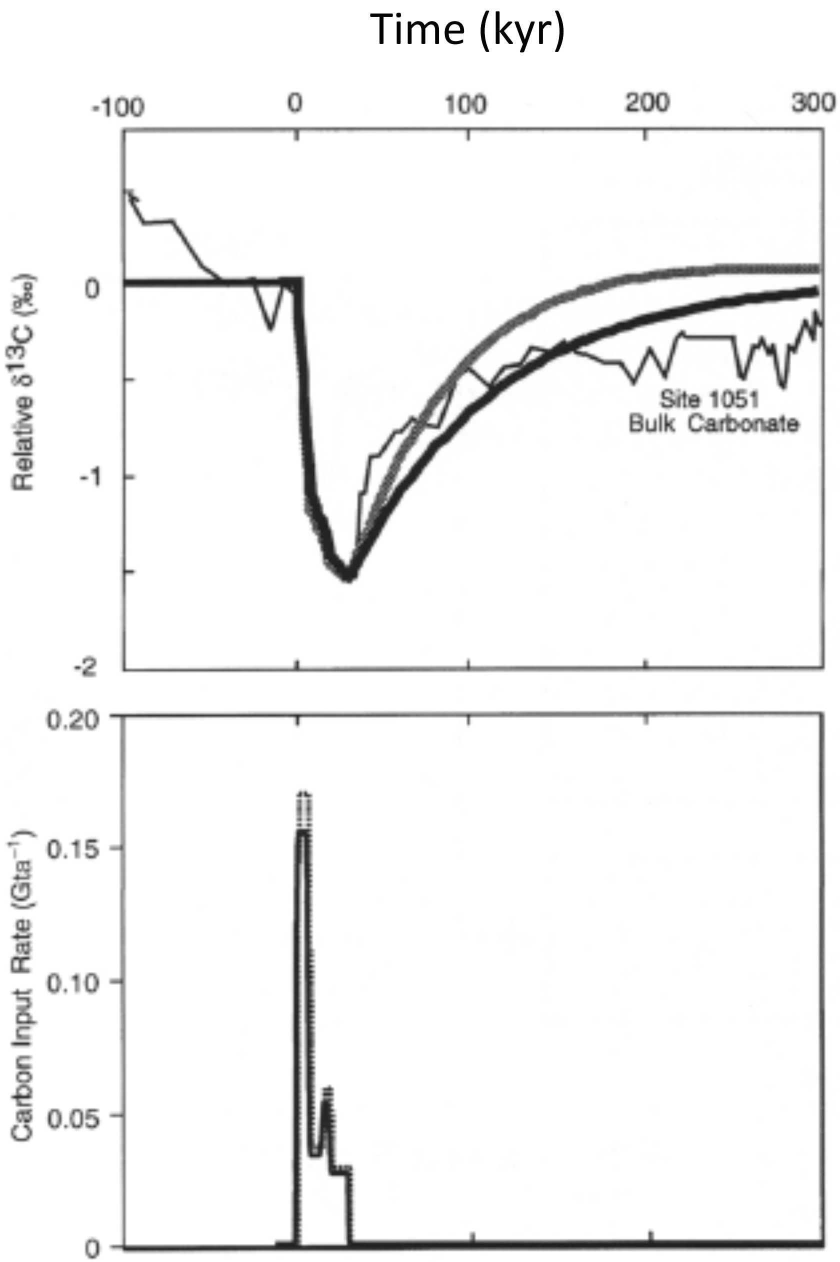




Generic Solutions

$F_{Add} = 2000\ Gt$
$\delta^{13}C_{Add} = -60‰$

Dickens, Geol. Soc. London, 2001



Specific Solutions

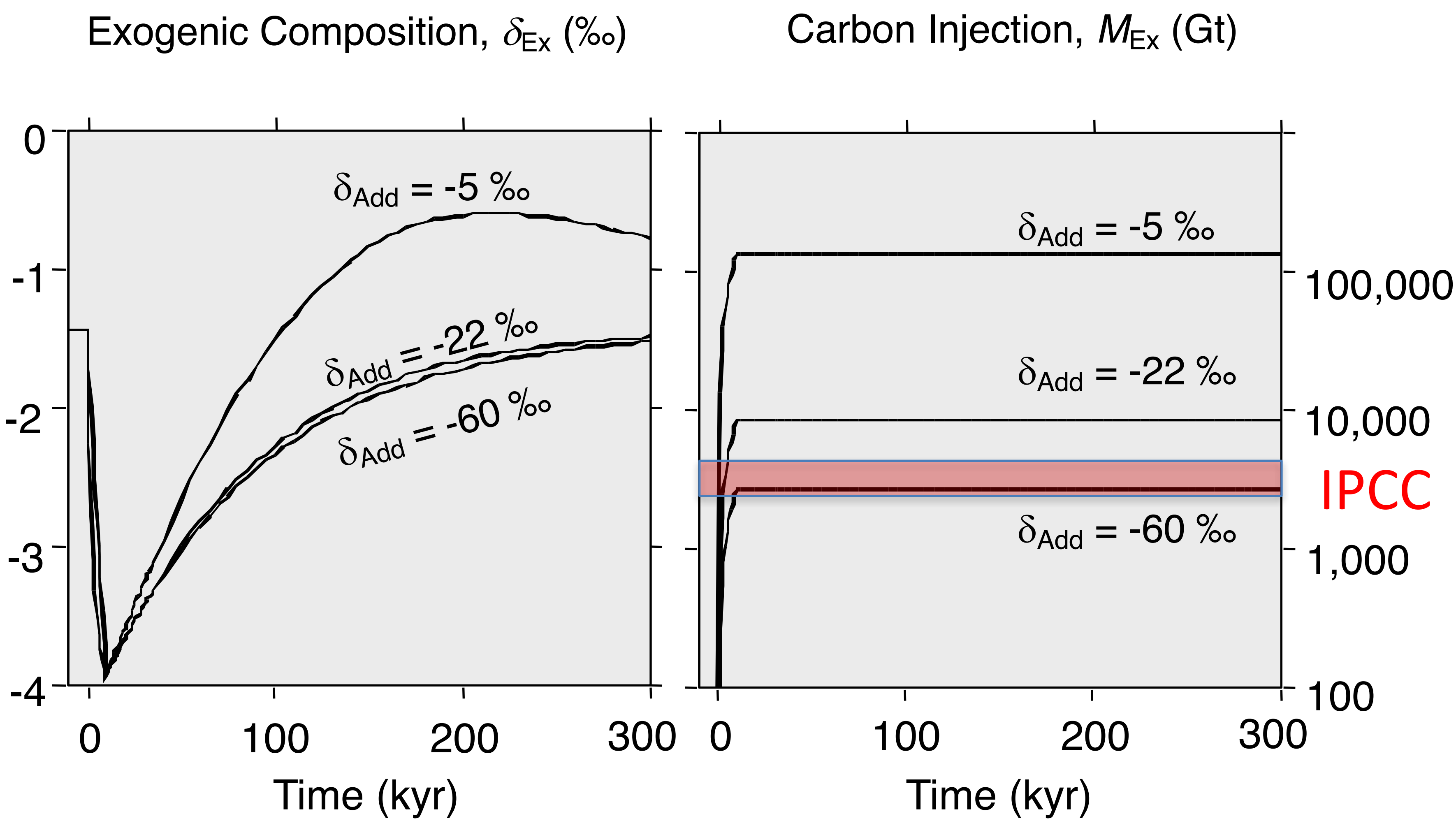
F_{Add} = 2000 Gt (pulsed over 10 kyr)

$\delta^{13}C_{Add}$ = -60‰

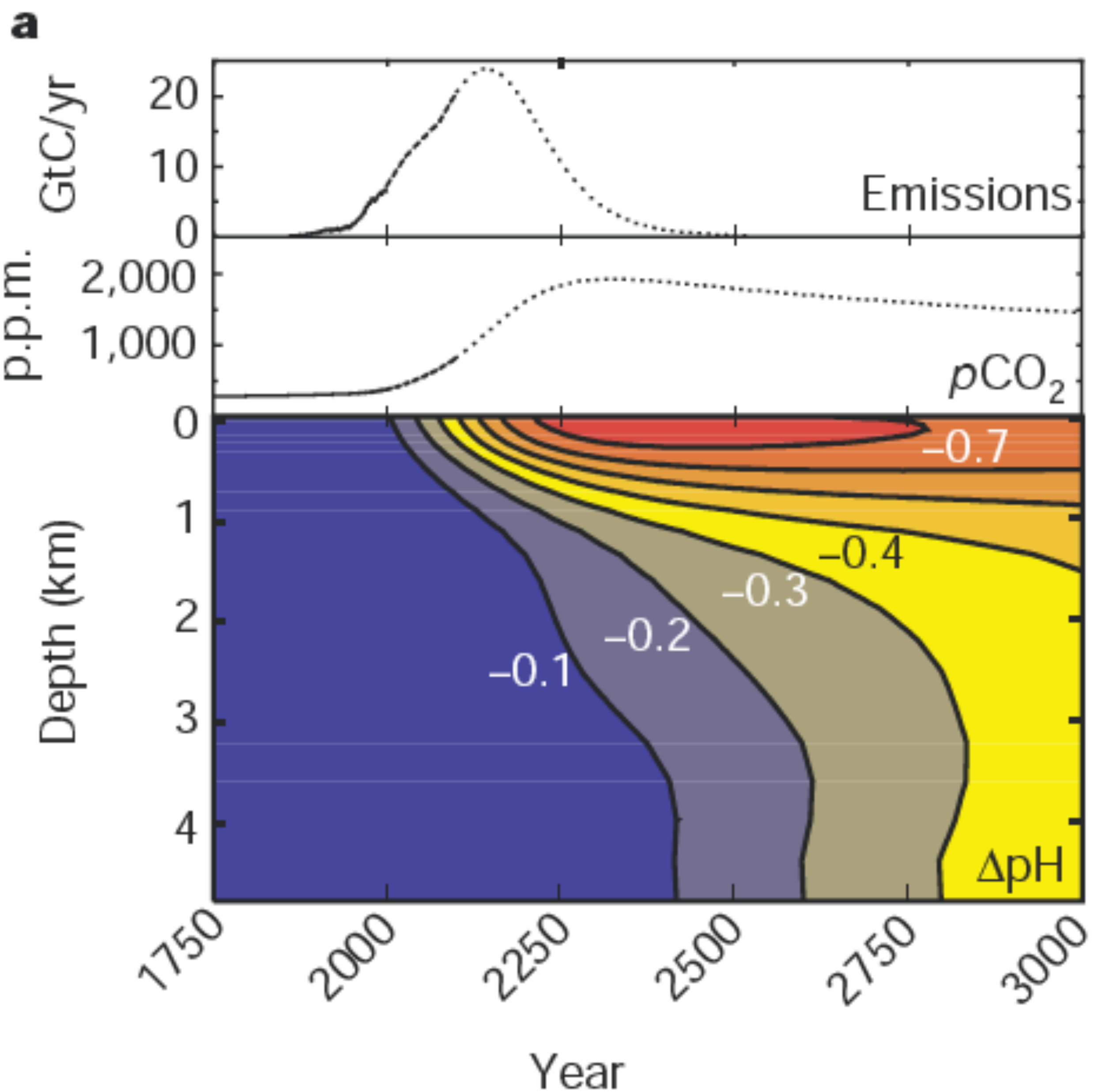
Dickens, Geol. Soc. London, 2001

7. Drowning in a real quandary

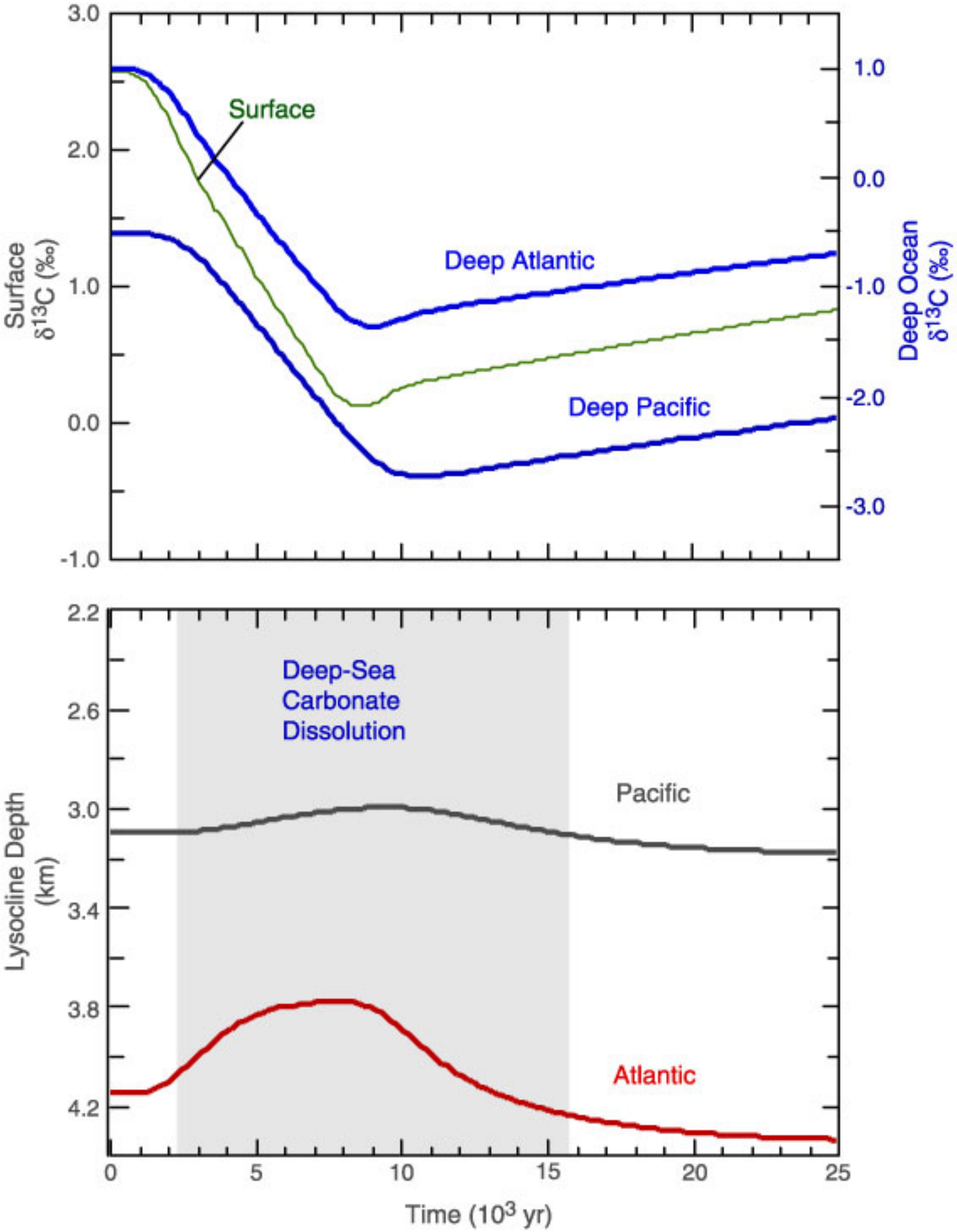
Theoretical Carbon Inputs for Rapid, Global, Negative $\delta^{13}C$ Excursions



Dickens, Geol. Soc. London, 2001



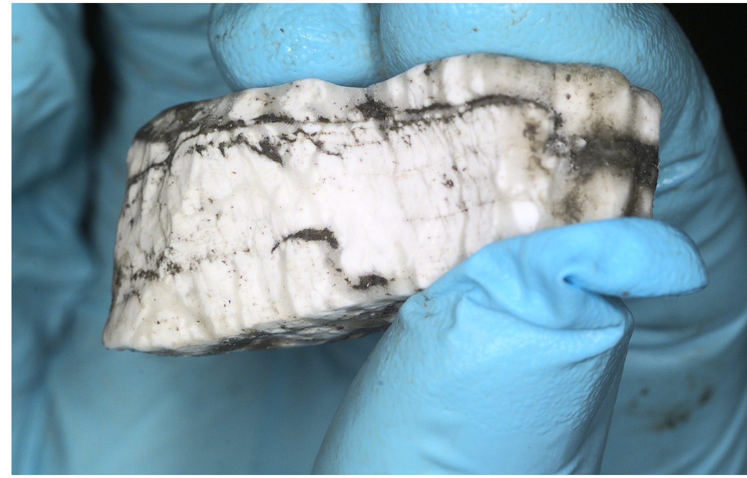
Ken Caldeira, Nature, 2003



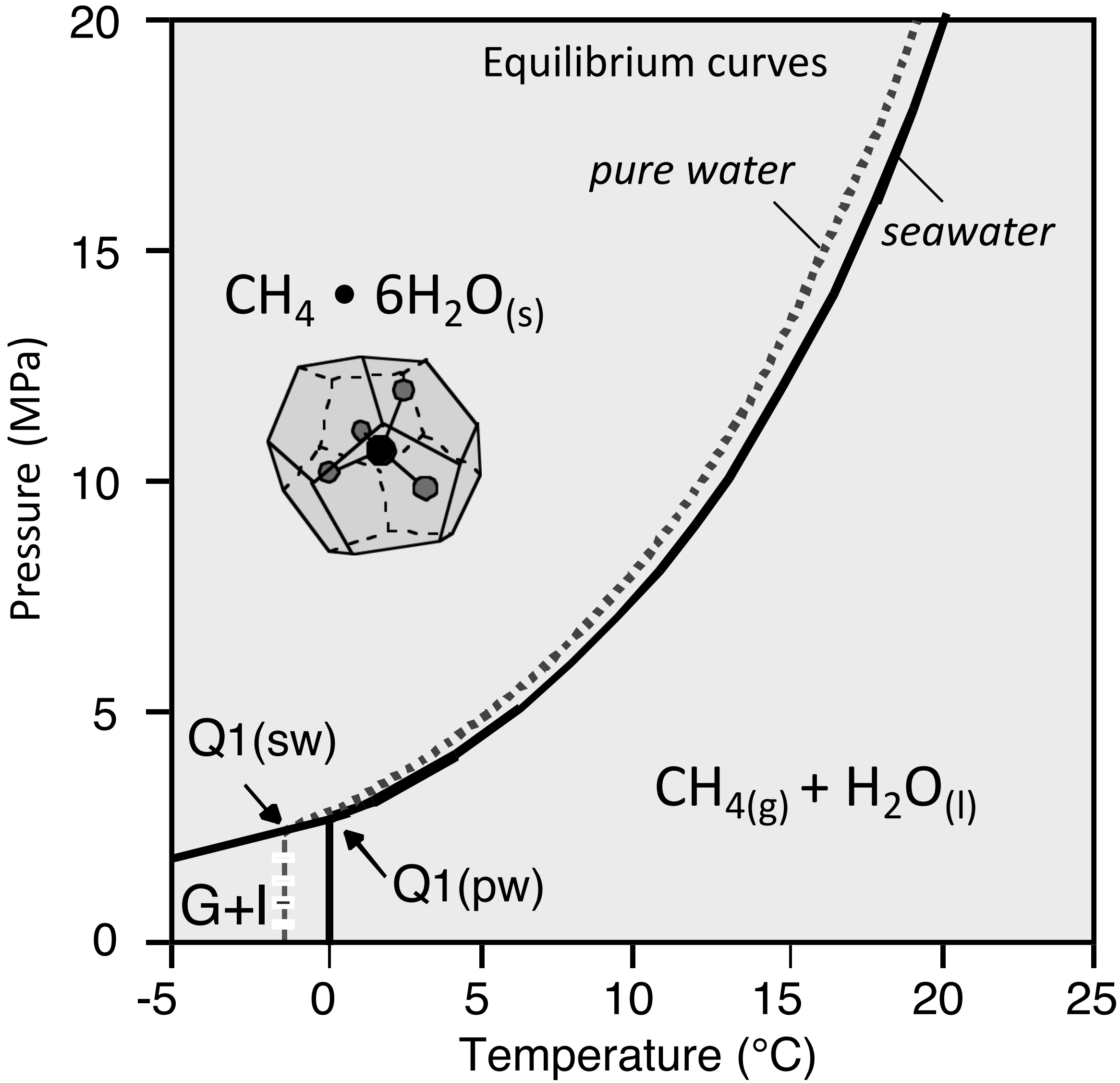
Dickens,
Bull. Soc. Geol. France, 2000

8. The Gas Hydrate Dissociation Hypothesis

Gas Hydrates Specimens ODP Leg 204: Hydrate Ridge



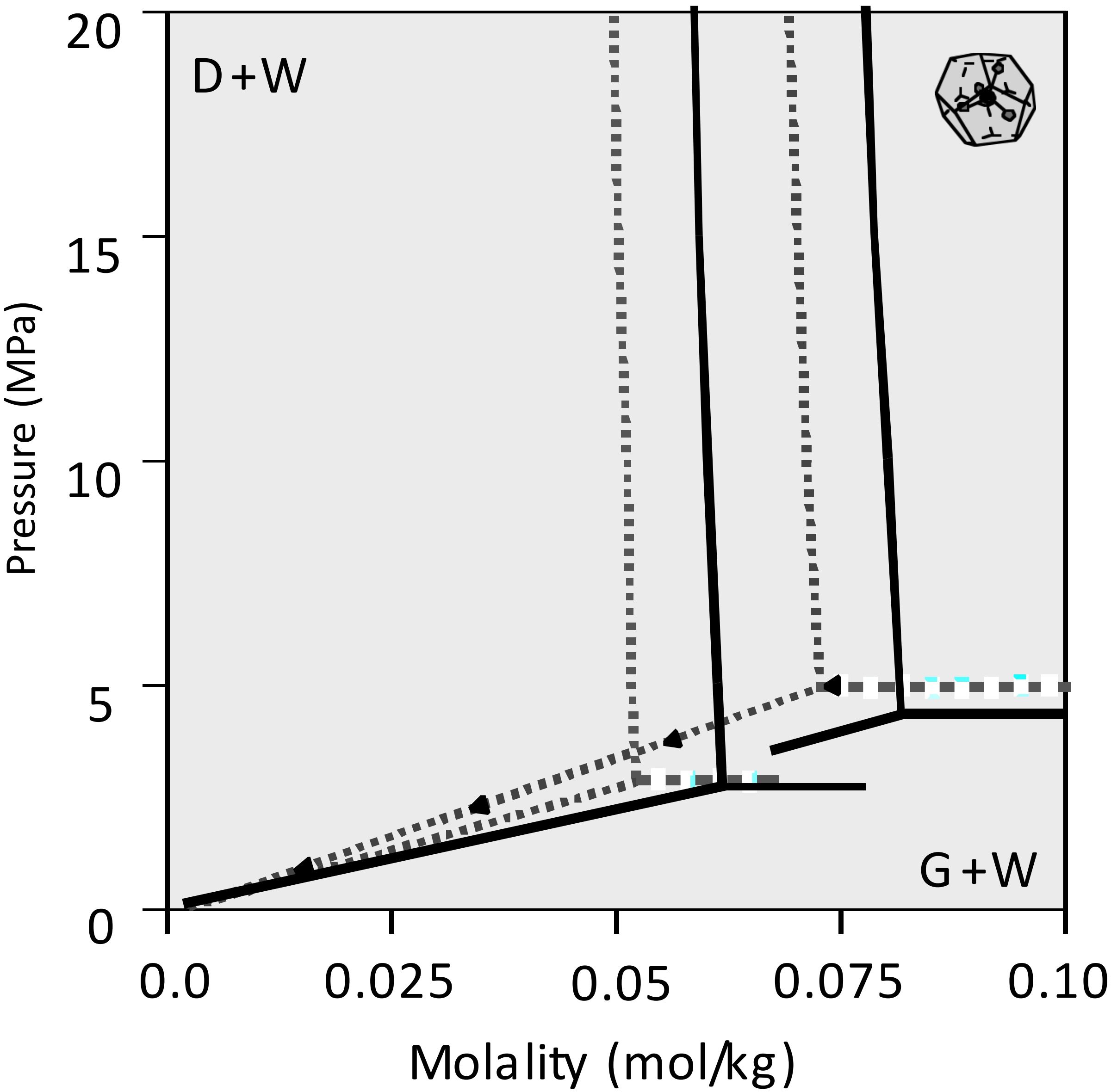
Methane Hydrate Stability: Pressure/Temperature



- *Moderate Pressure*
- *Low Temperature*

Dickens & Quinby-Hunt, GRL, 1994

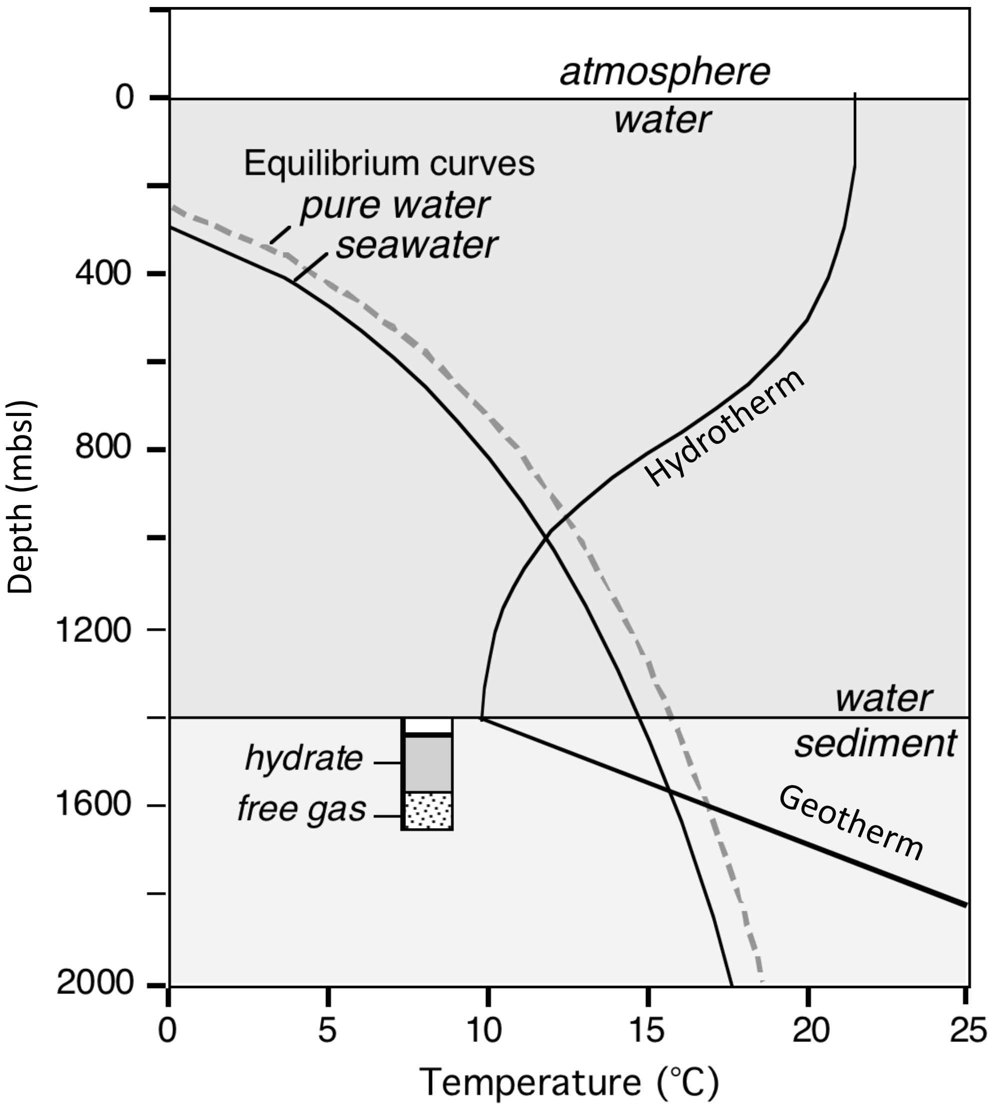
Methane Hydrate Stability: Gas Concentration



- *Sufficient Gas*

Handa, J. Phys. Chem., 1990

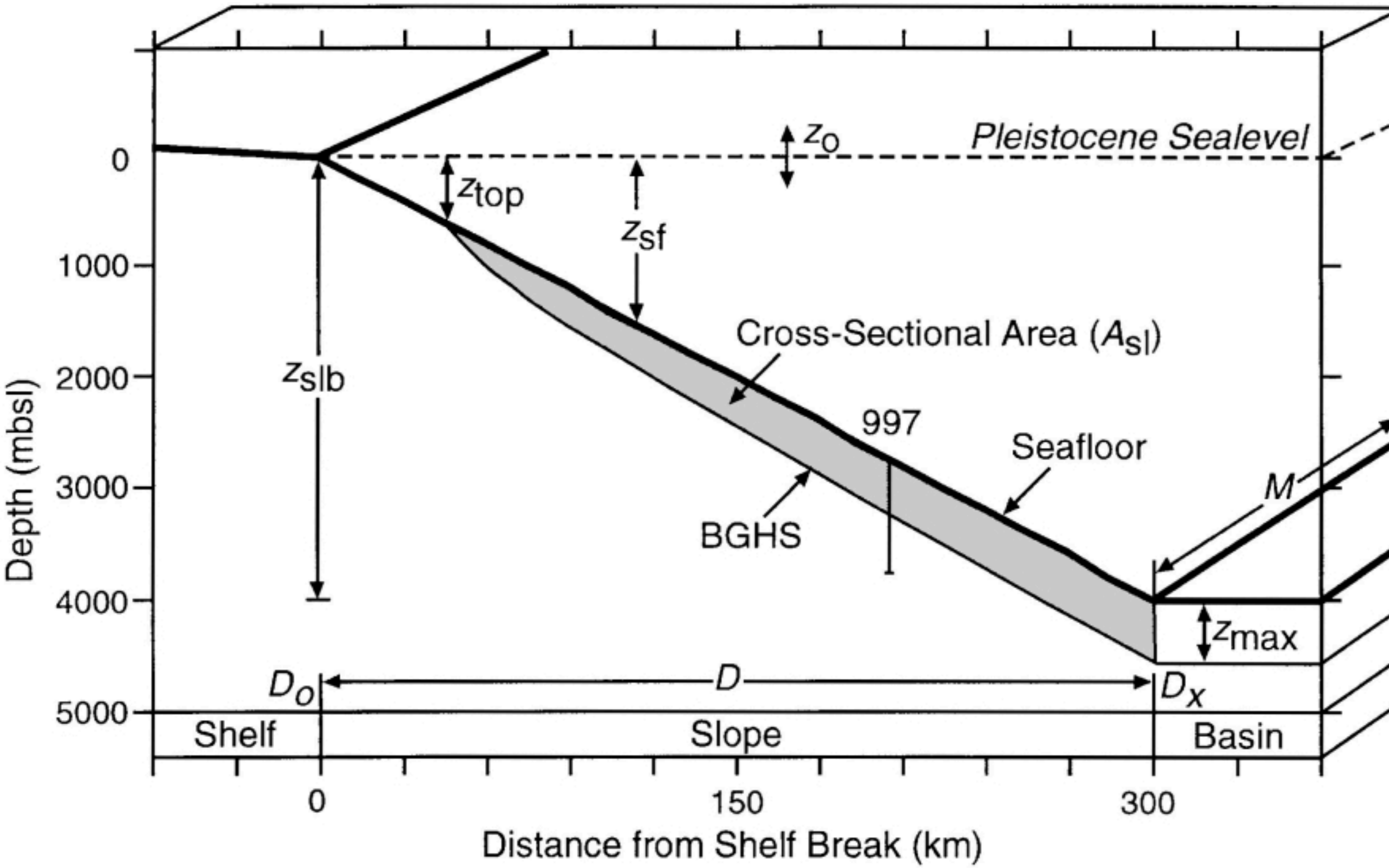
Gas Hydrate Distribution with 10°C Bottom Water



- Shallow Sediment in Deep Water
- High Gas Fluxes

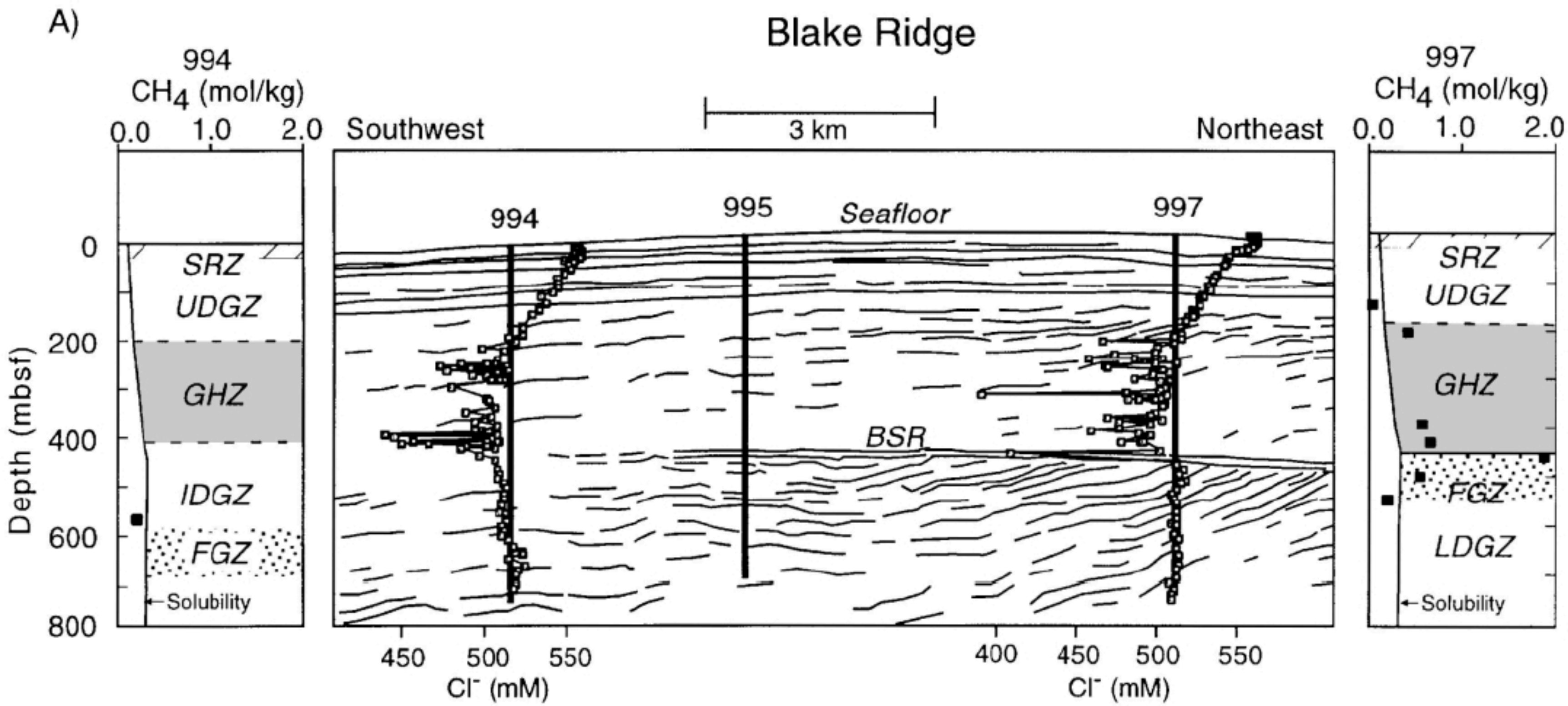
Dickens & Quinby-Hunt, JGR, 1997

Potential Volume of Gas Hydrate



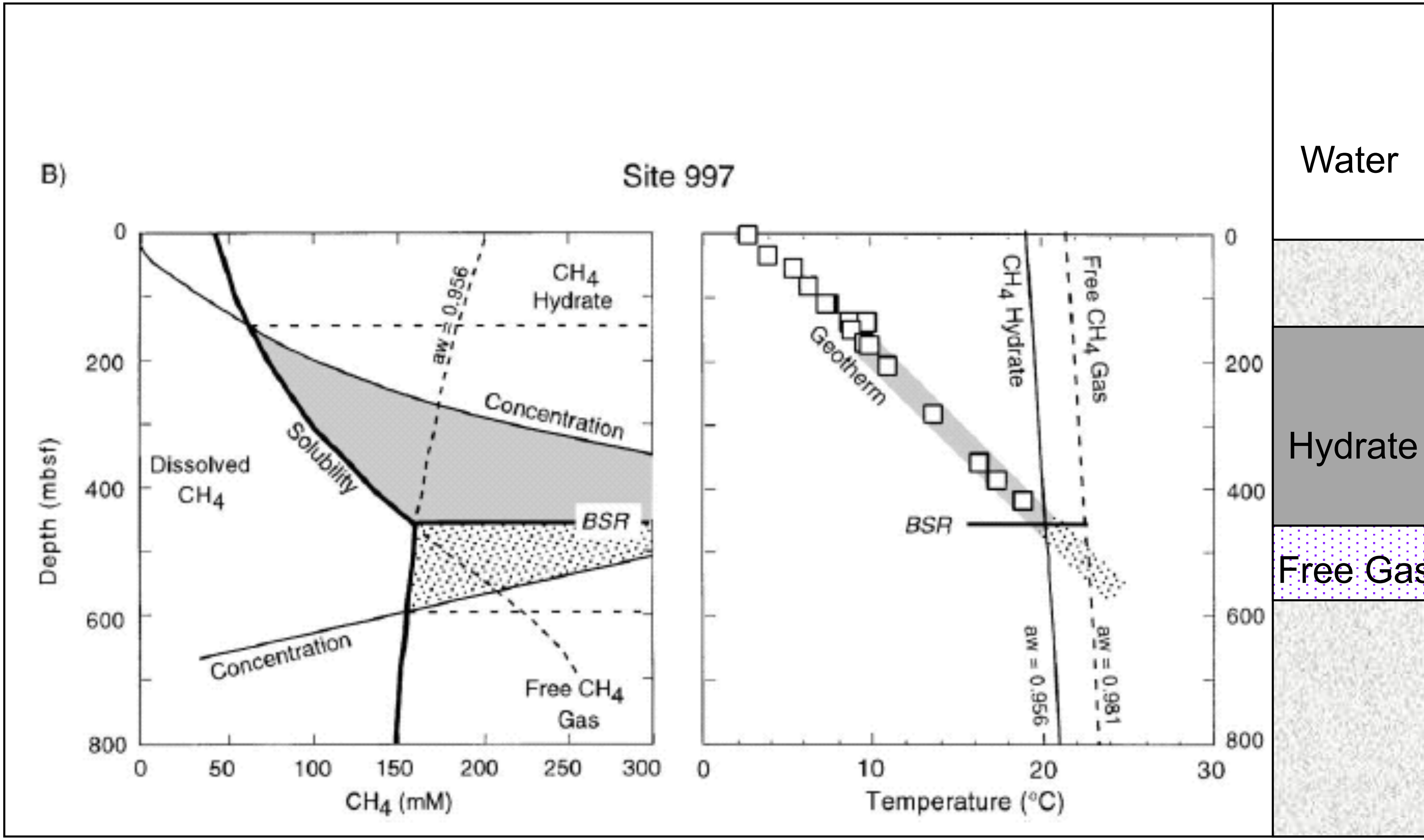
Dickens, Organic Geochemistry, 2001

Blake Ridge: A fairly well-constrained gas hydrate system



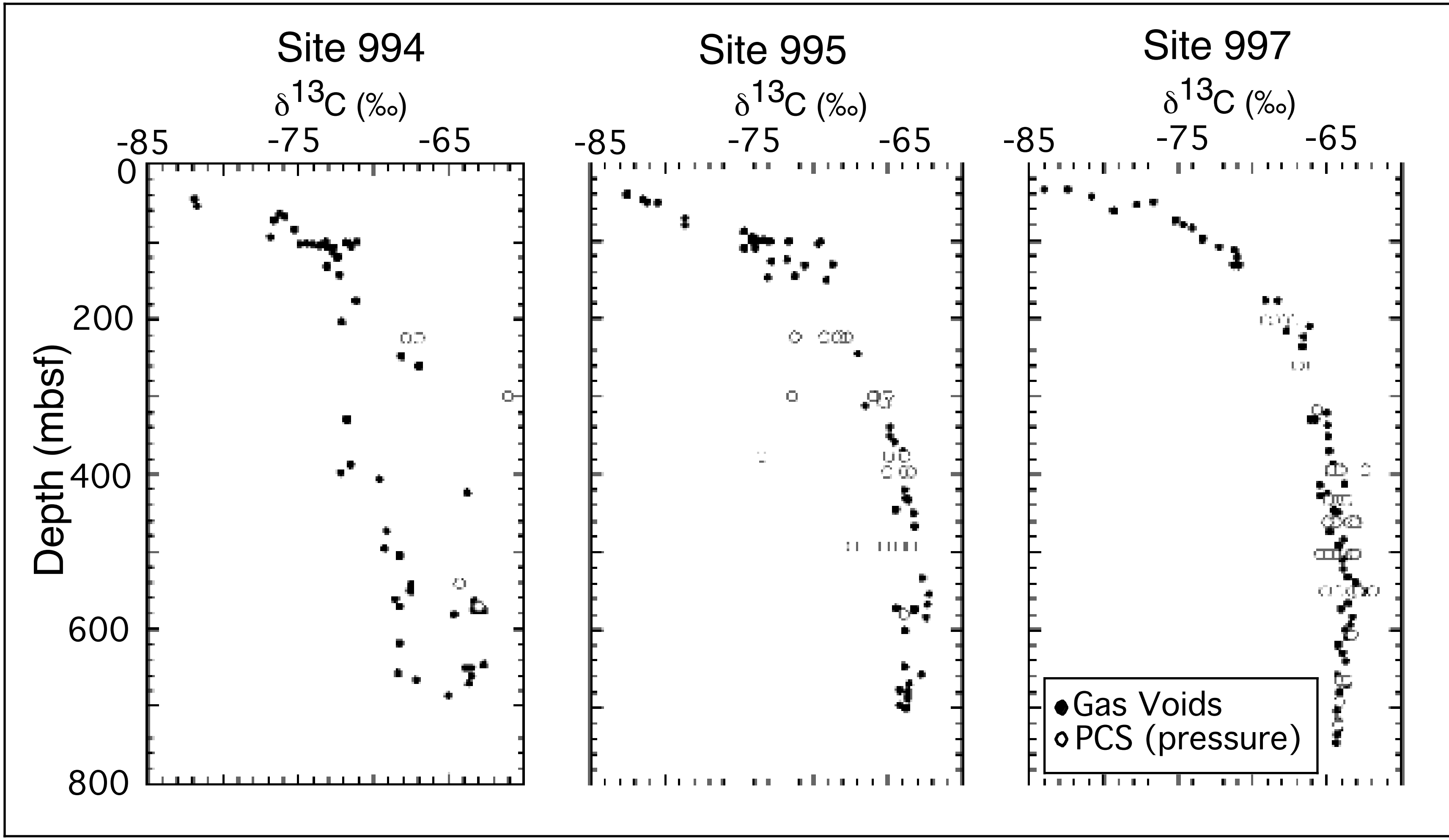
Dickens, Org. Geochemistry, 2001

Where Gas Hydrates Occur in Marine Sediment



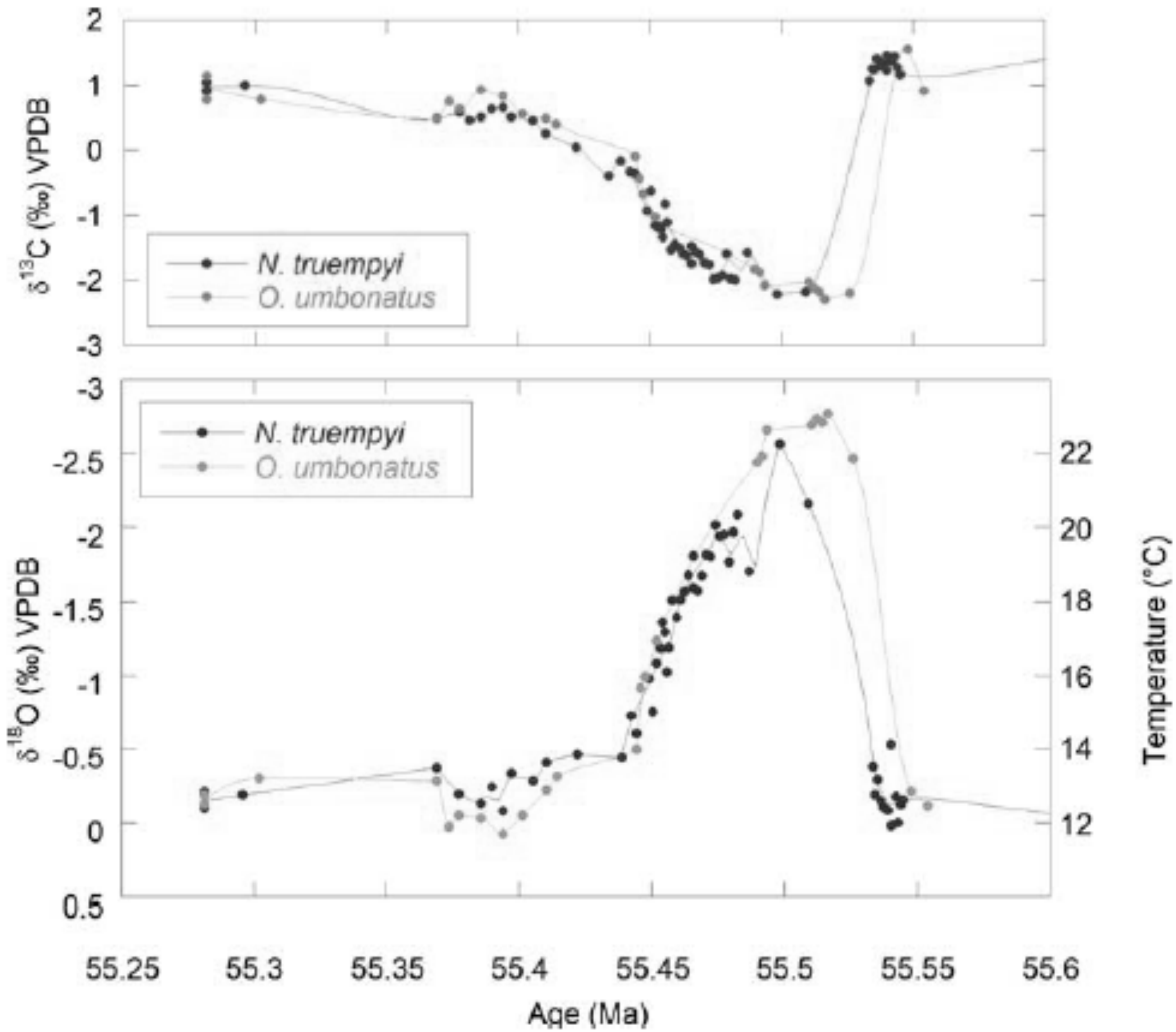
Source: *Dickens, Org. Geochem., 2001*

Isotopic Composition of Gas on the Blake Ridge



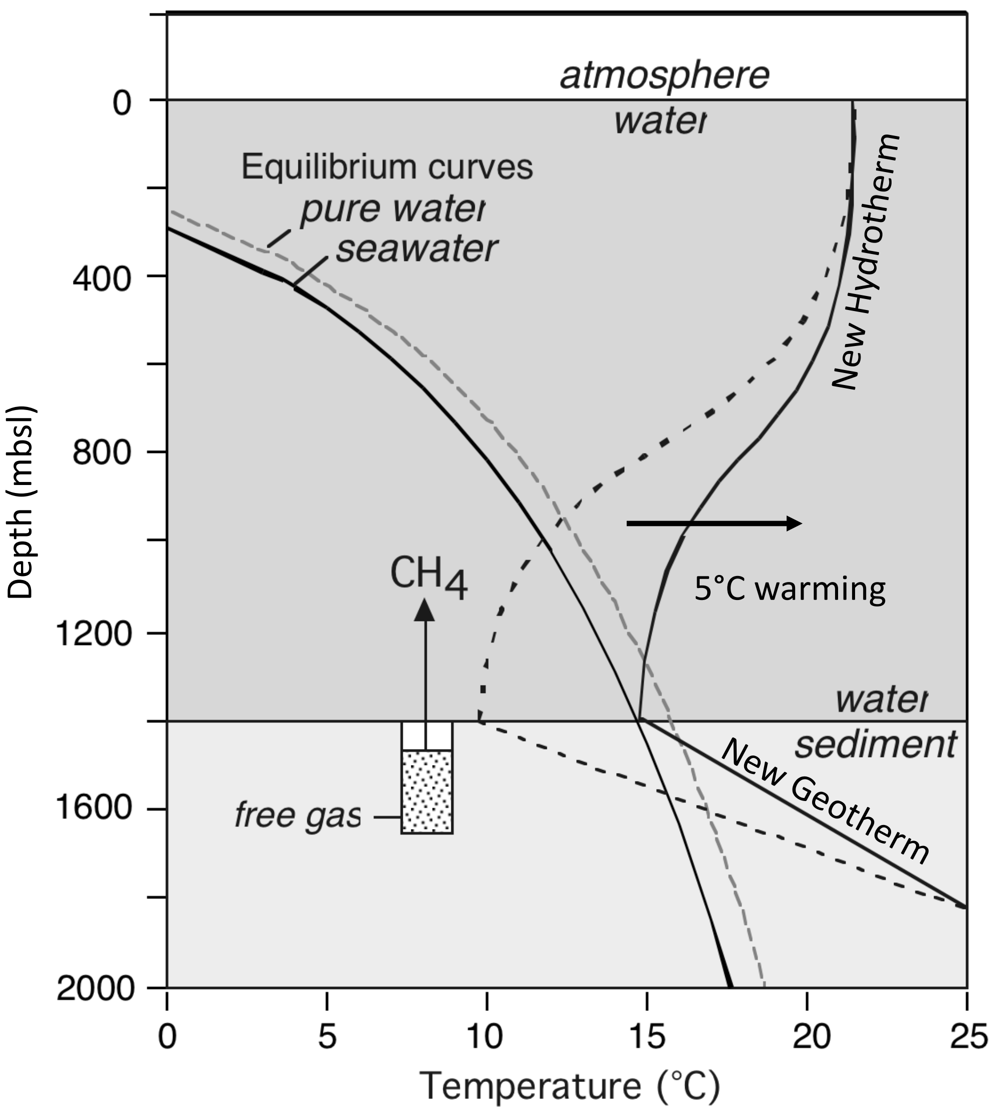
Source: *Wallace et al., Proc. ODP, 2000*

Evidence for Deep Ocean Warming: Benthic Forams



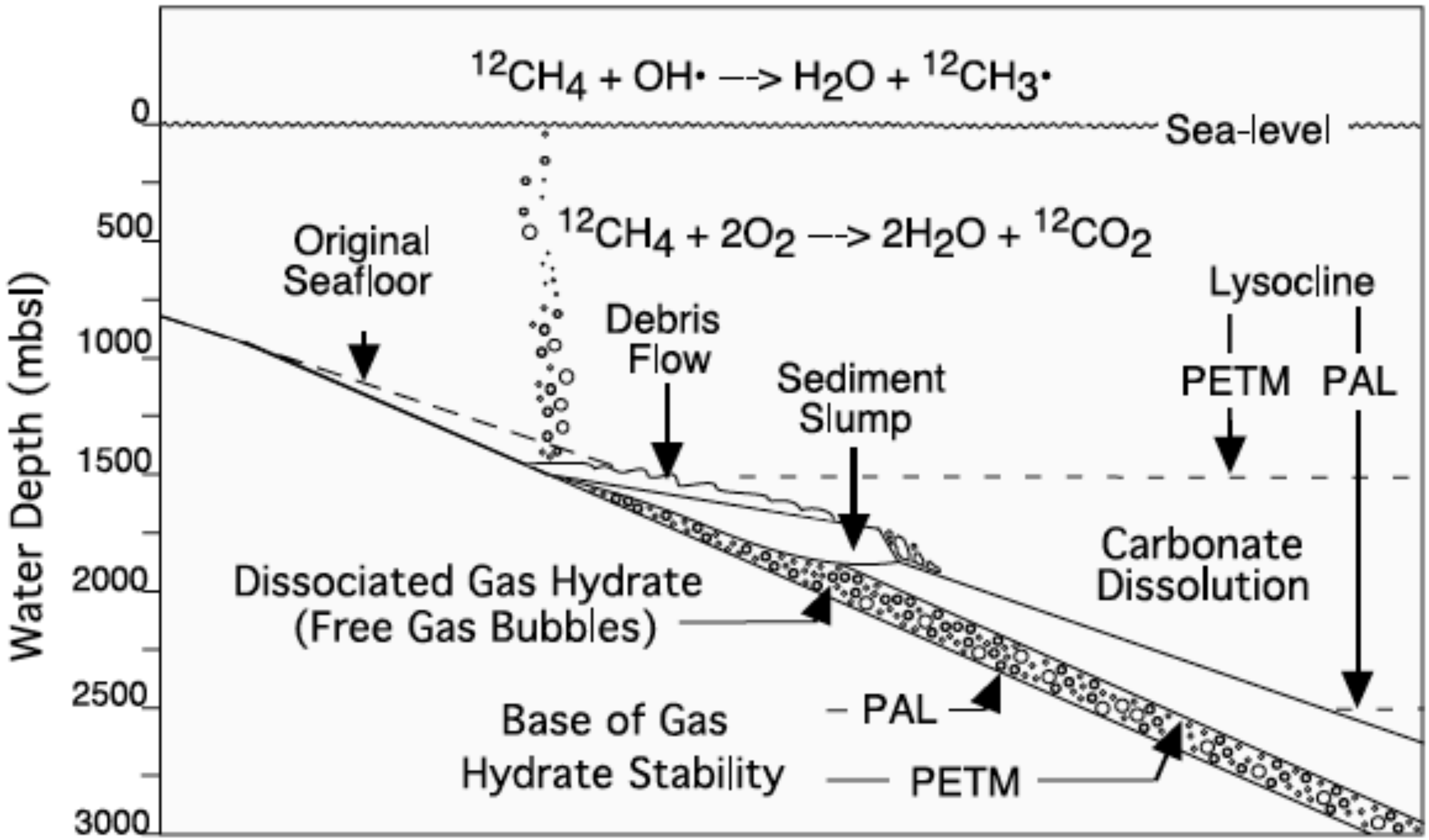
McCarren et al., G3, 2008

Gas Hydrate with a 5°C Temperature Change

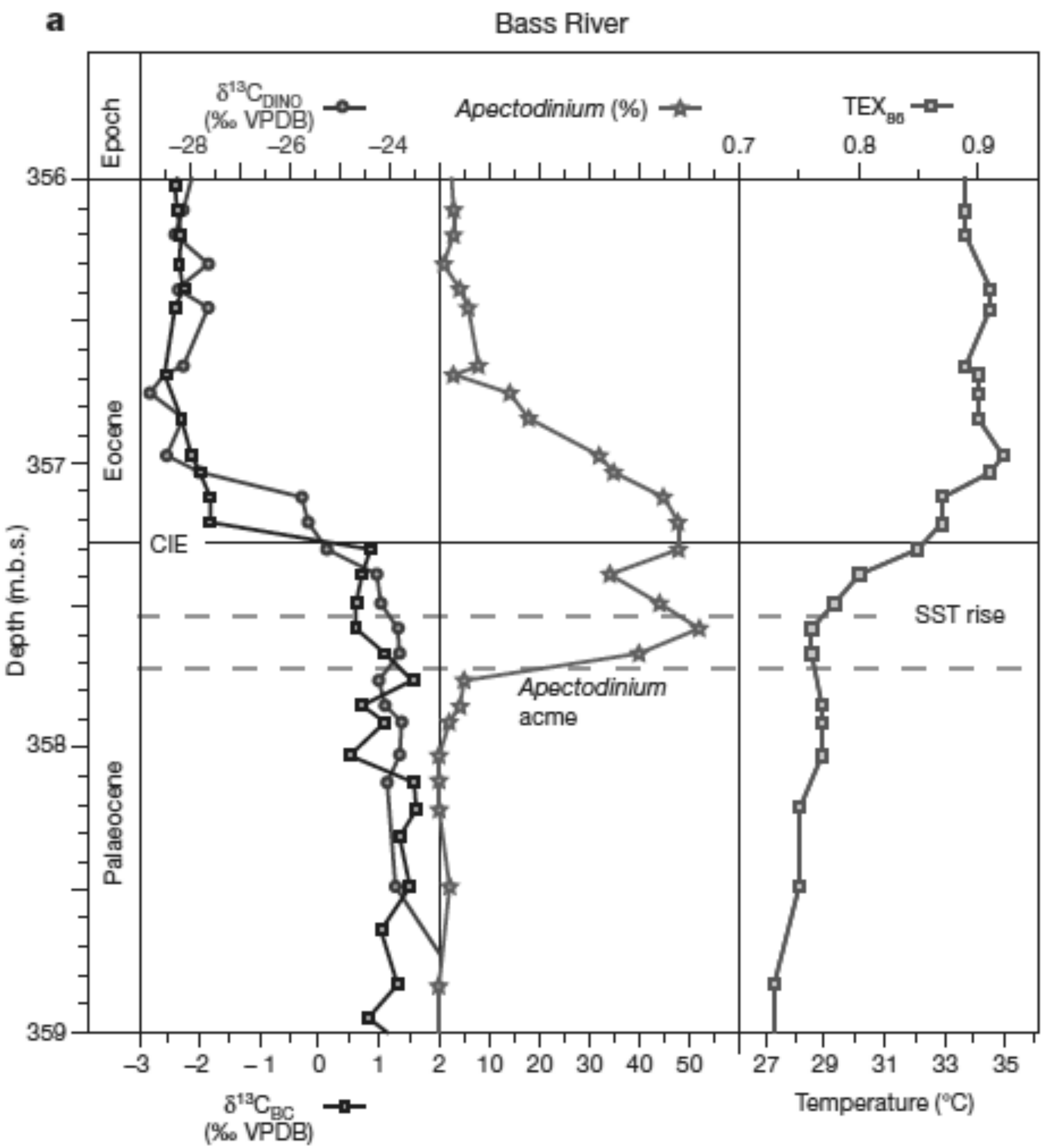


- Thermal Dissociation of Gas Hydrate
- Methane release

Gas Hydrate with a 5°C Temperature Change

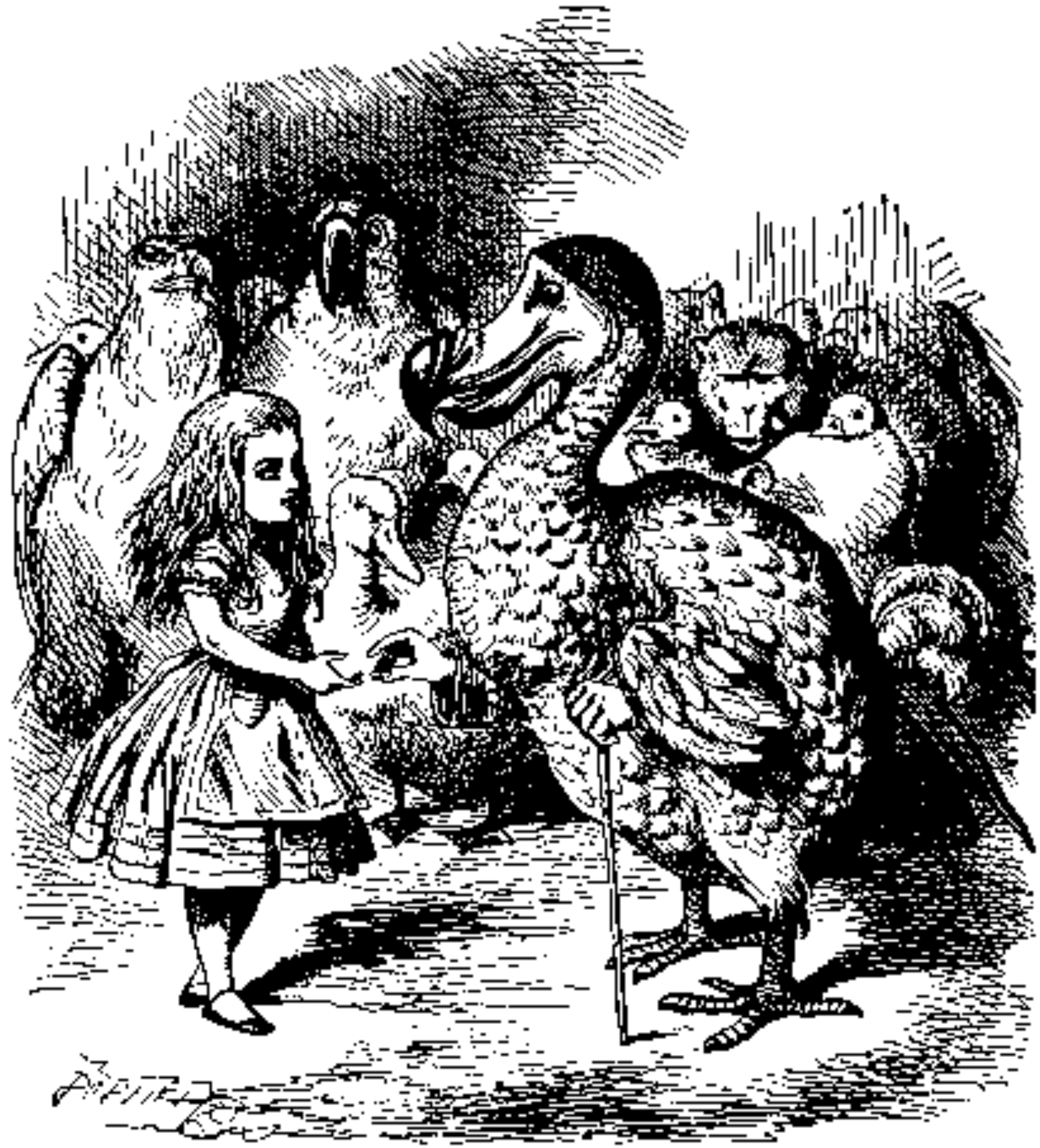


Dickens, EPSL, 2003 (after modifications from McIver, 1990 & Katz et al., 1999)

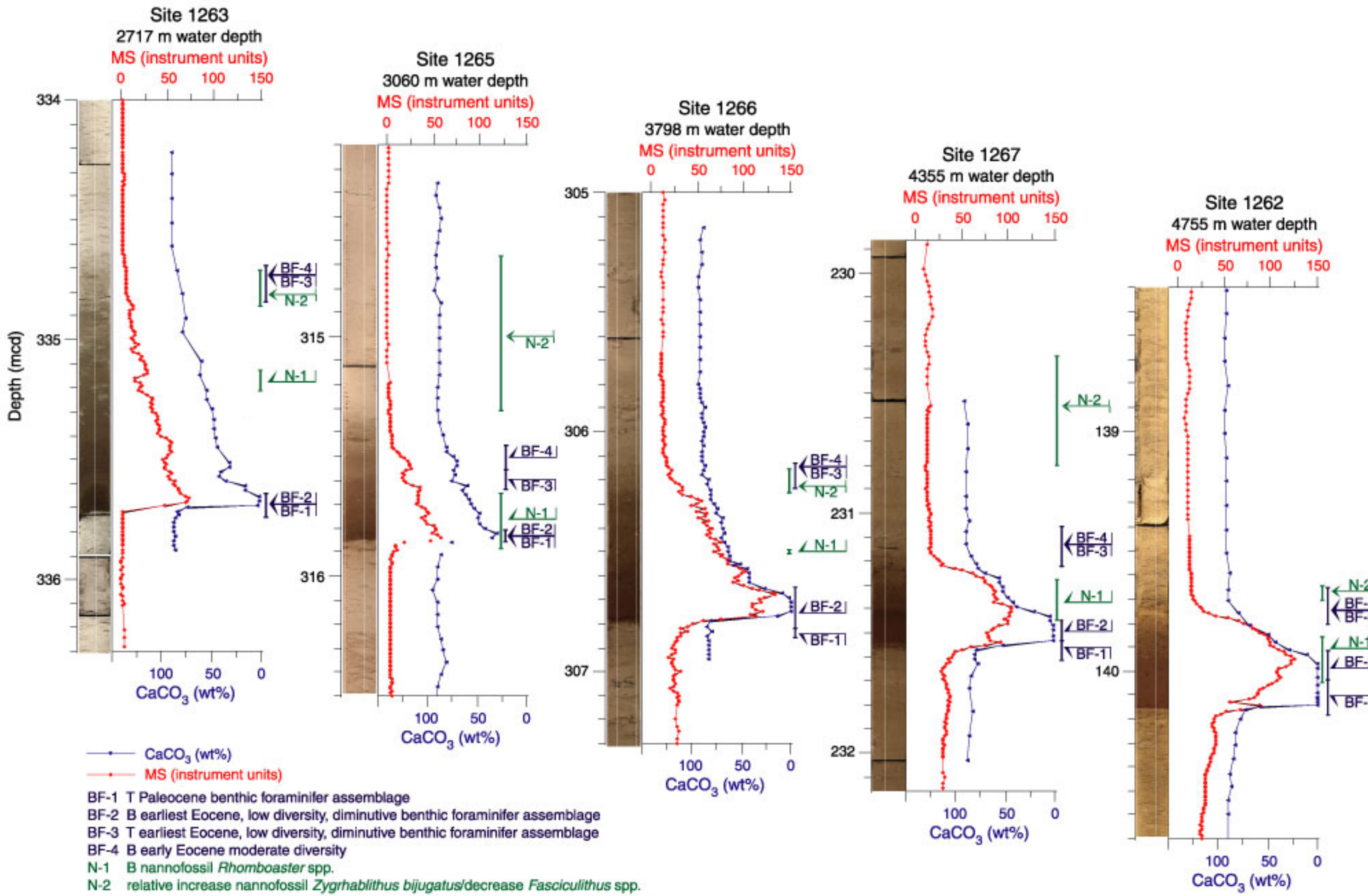


Sluijs et al., Nature, 2007

9. *Presenting the basics behind the idea*

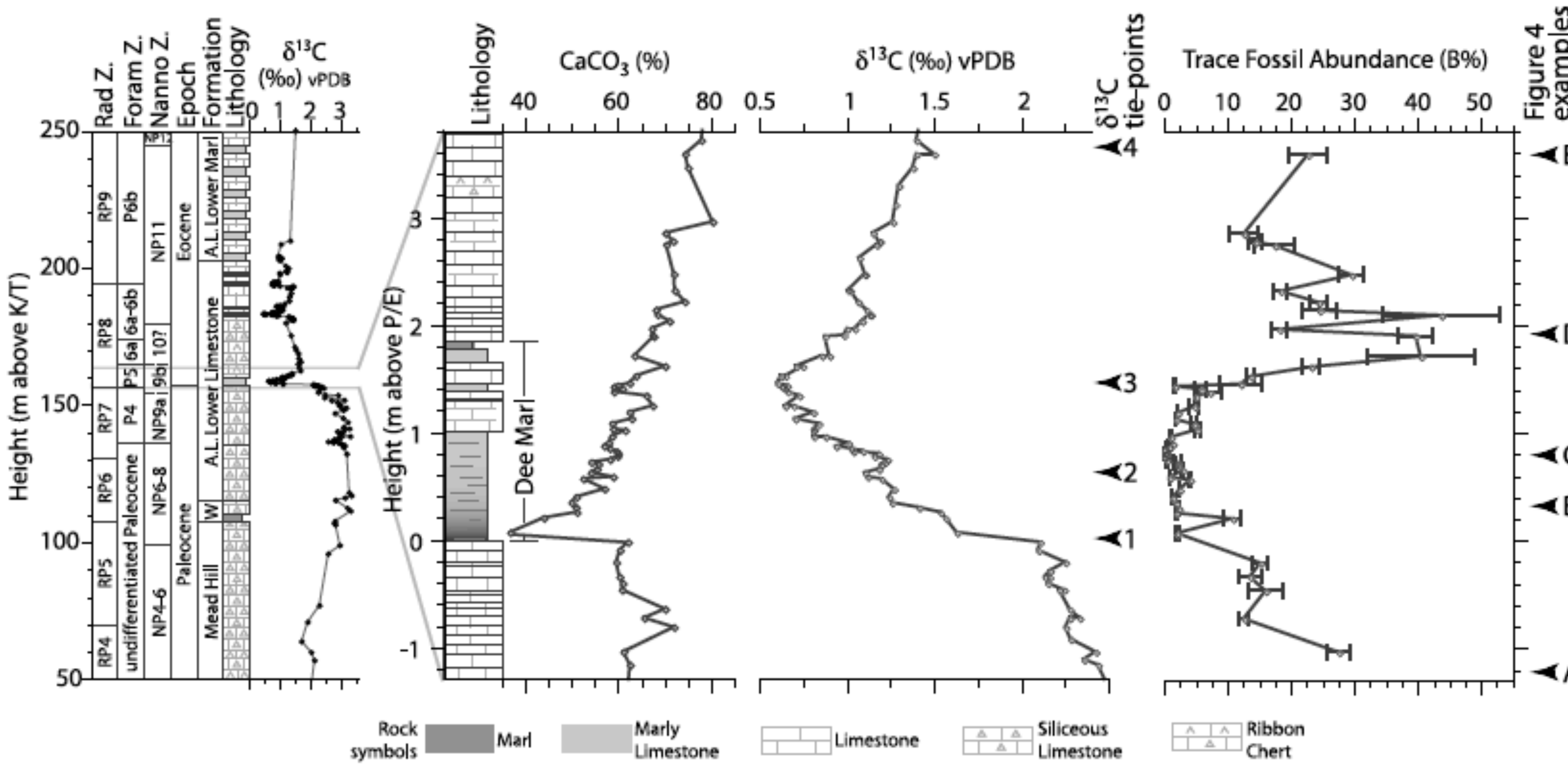


PETM at Walvis Ridge (Central Atlantic)



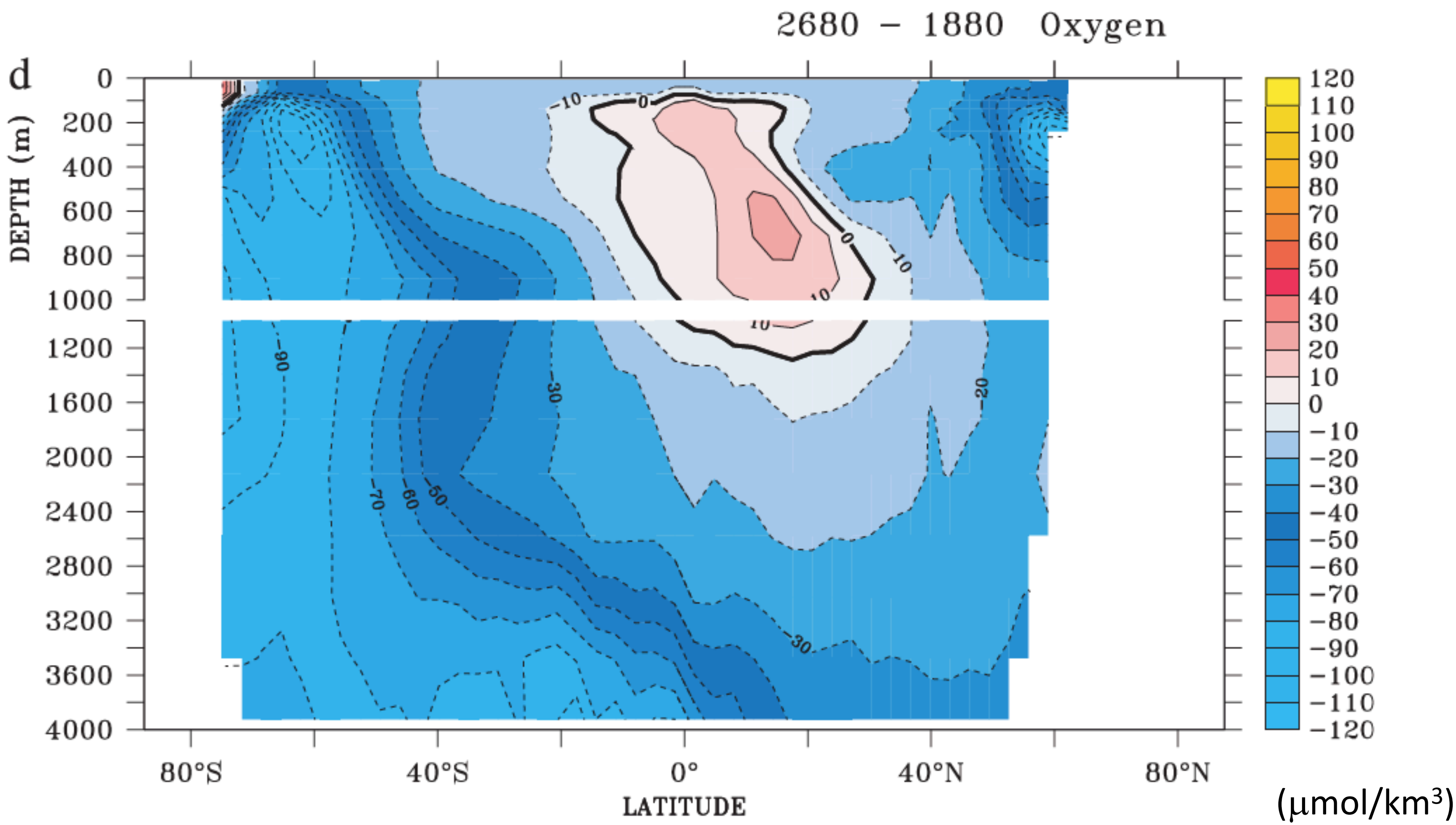
Zachos et al., Proc ODP Init. Repts., 208, 2004

Bioturbation Record at Mead Stream (New Zealand)



Nicolo et al., Paleoceanography, 2010

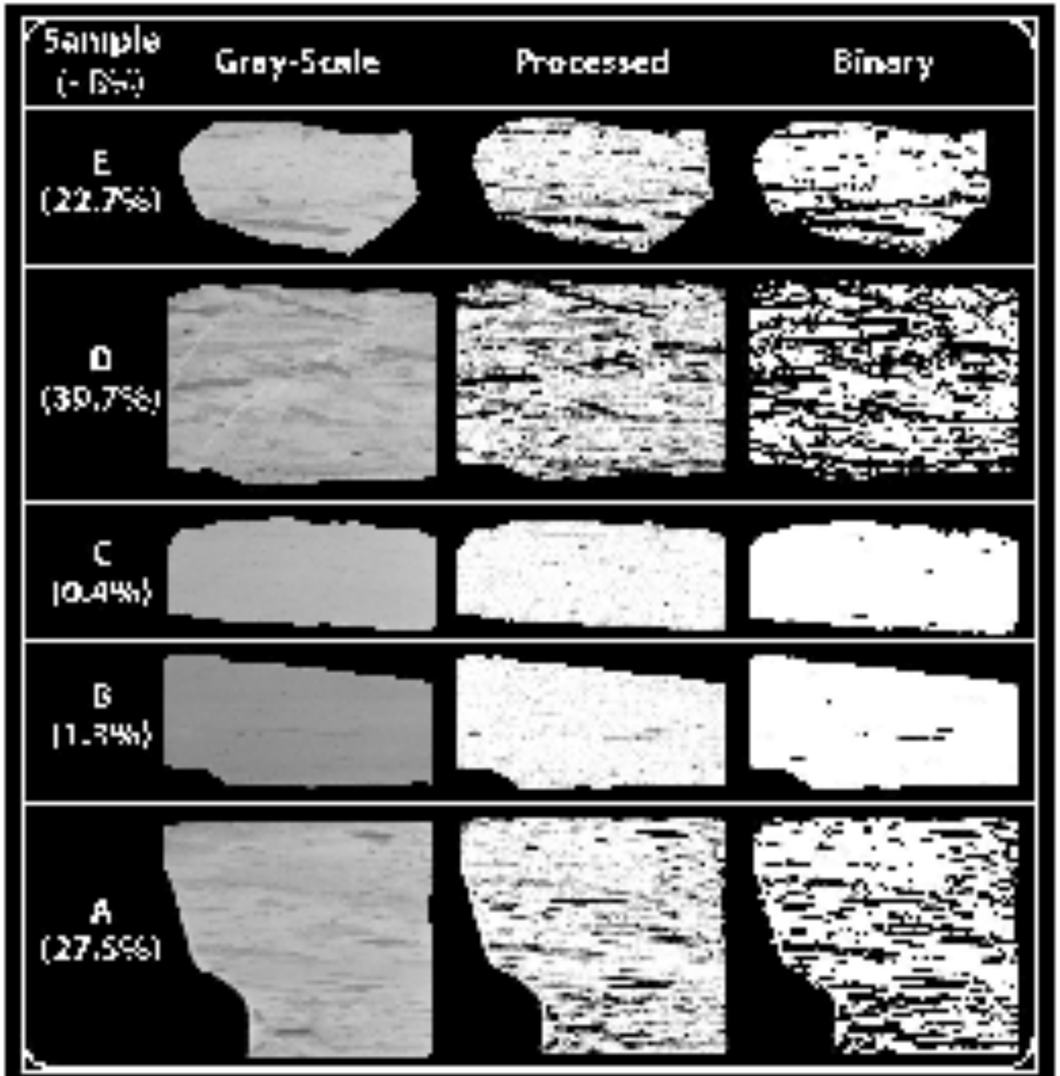
Predicted Change in Pacific Dissolved Oxygen by AD 2680

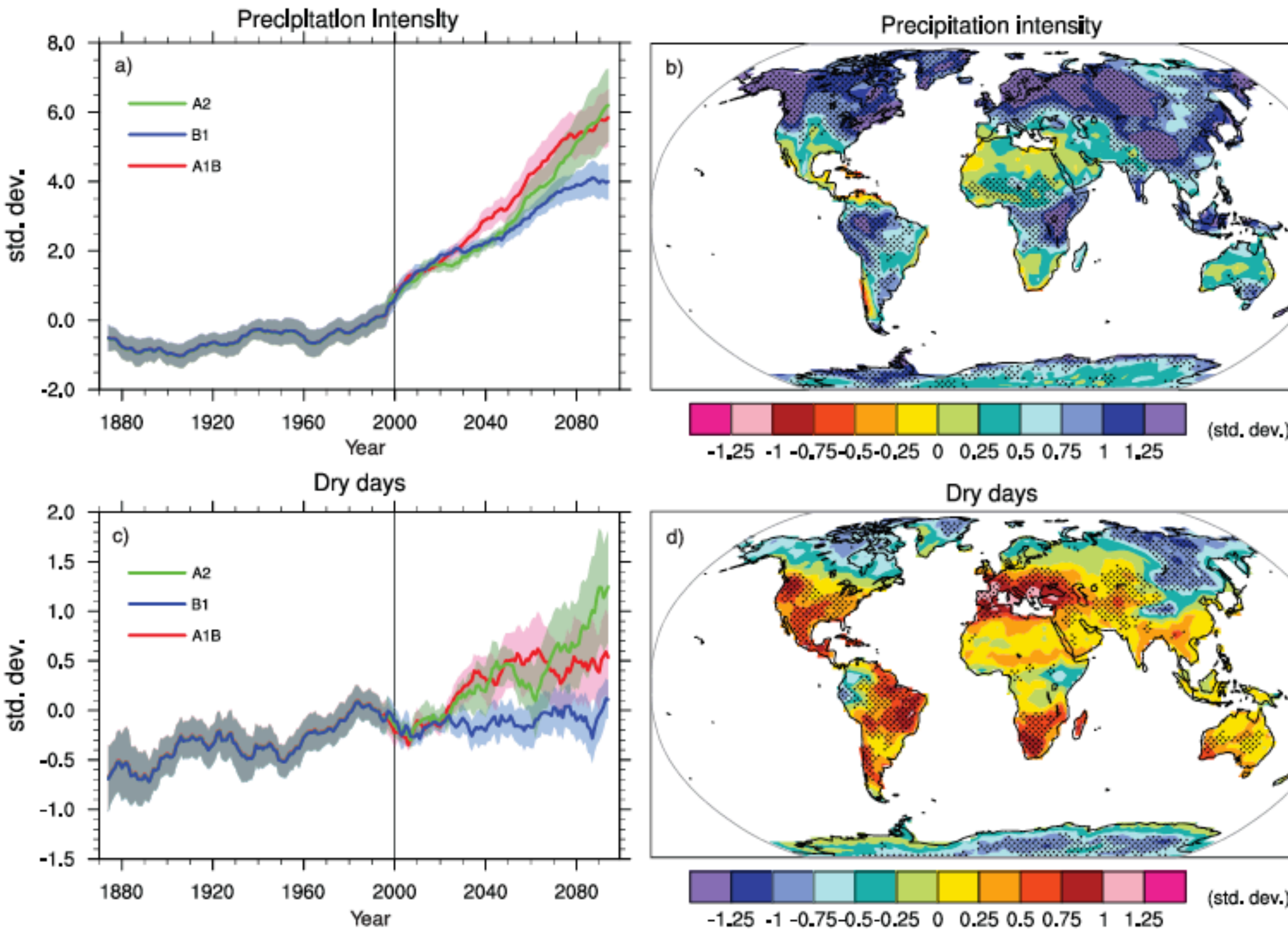


[*Matear & Hirst, Global Biogeochemical Cycles, 2003*]

Bioturbation Record at Mead Stream (New Zealand)

Figure 4. Bioturbation image processing and analysis

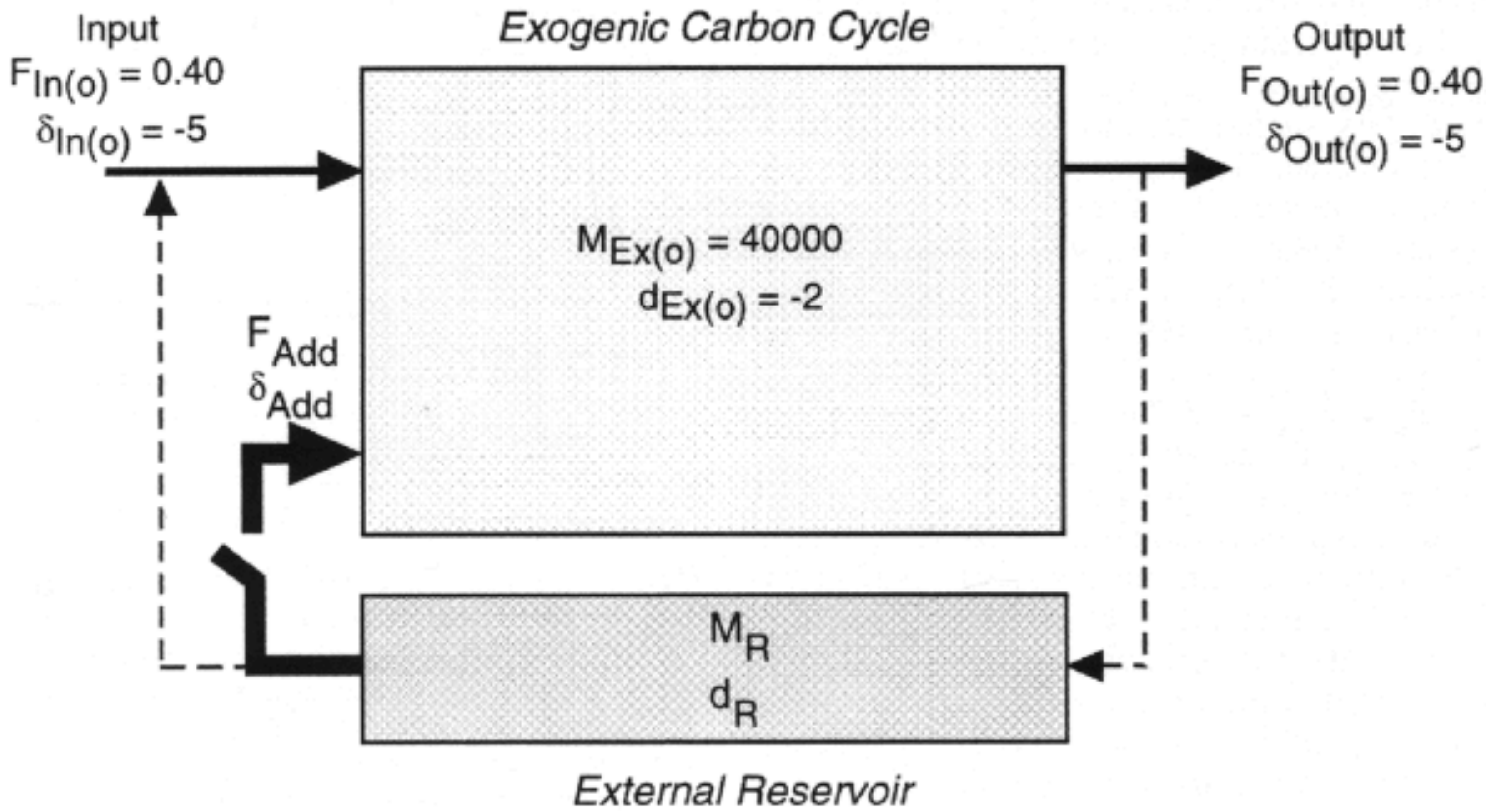



Precipitation Intensity
a)
A2
B1
A1B
std. dev.
8.0
6.0
4.0
2.0
0.0
-2.0
1880 1920 1960 2000 2040 2080
Year
Precipitation intensity
b)
-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25
(std. dev.)
Dry days
c)
A2
B1
A1B
std. dev.
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1880 1920 1960 2000 2040 2080
Year
Dry days
d)
-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25
(std. dev.)

[*IPCC, 2007*]

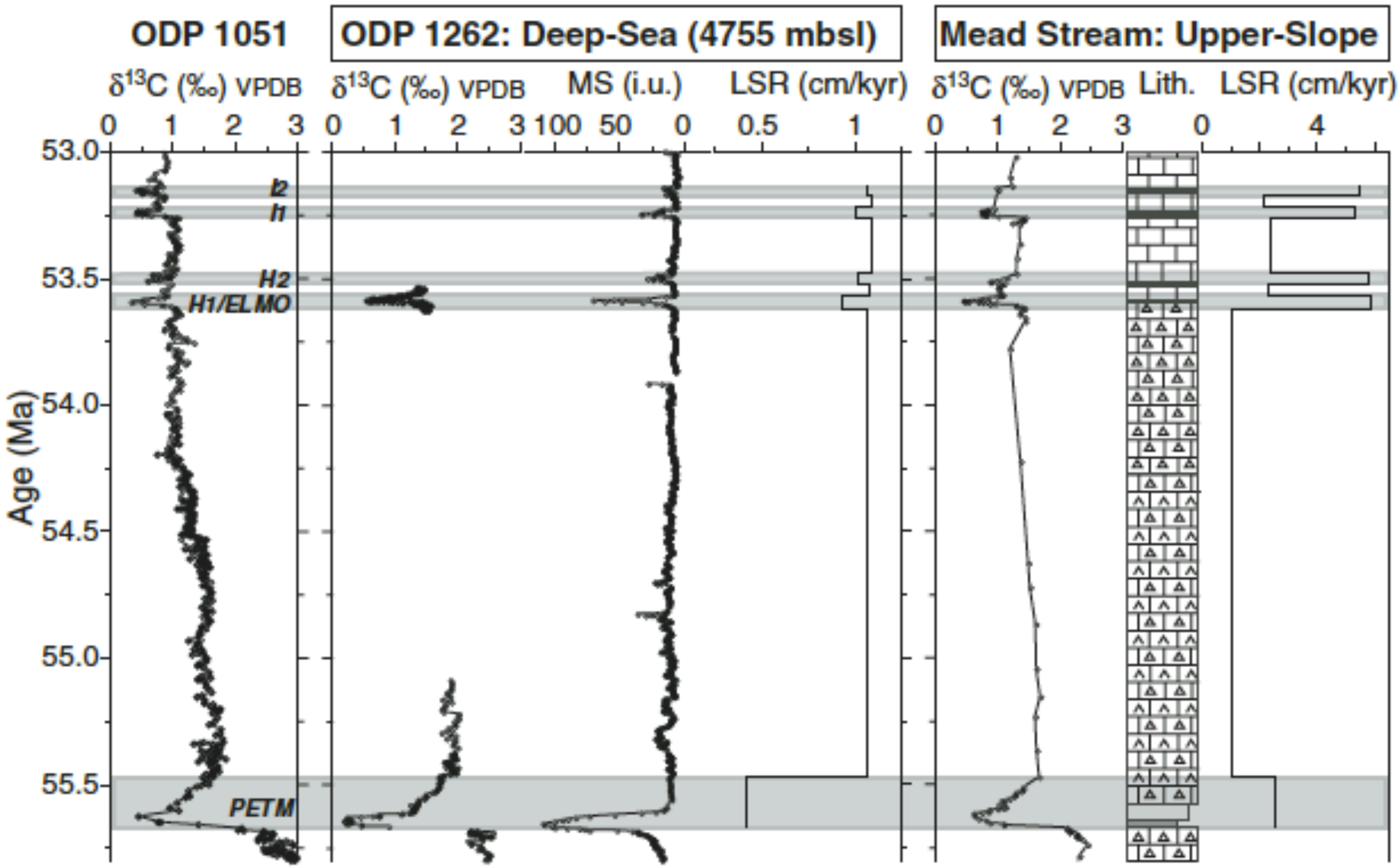
A Capacitor: Simple Model for a Global Carbon Isotope Excursion

Masses in Gigatonnes; Fluxes in Gt/yr; Delta in per mil



Dickens, Geol. Soc. London, 2001

Multiple Hyperthermal Events

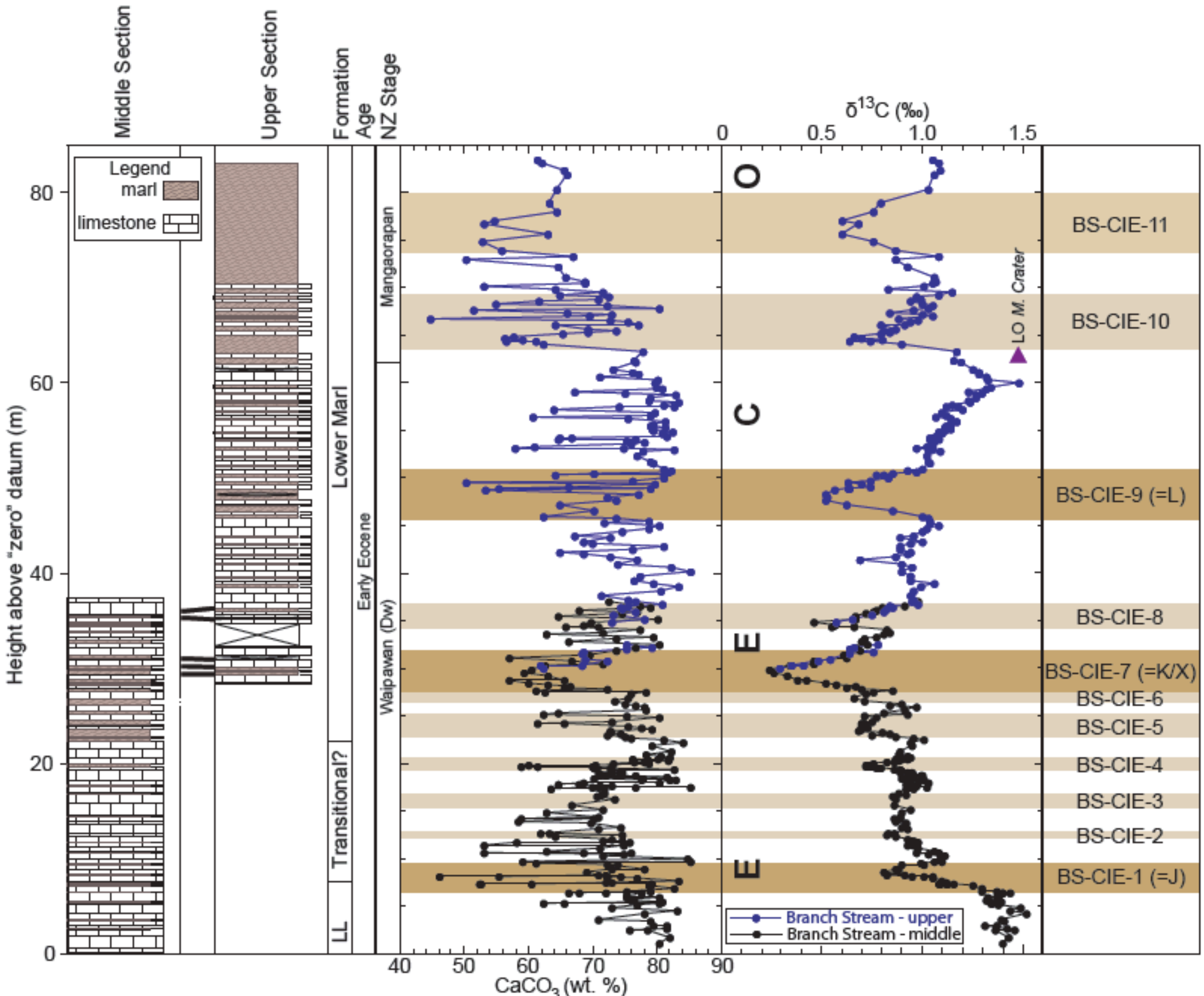


Nicolo et al., Geology, 2007

Branch Stream, New Zealand

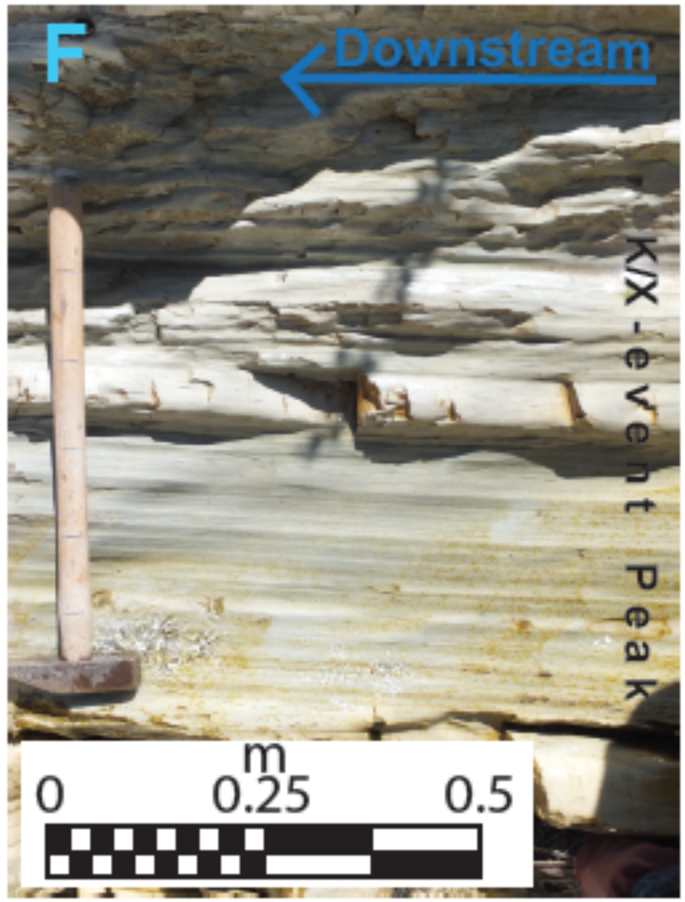
Slotnick et al., NZJGG, 2015

Branch Stream, New Zealand



Slotnick et al., NZJGG, 2015

Branch Stream, New Zealand



Slotnick et al., NZJGG, 2015

10. Colleagues Arguments Against Gas Hydrate Dissociation

The warming across the PETM (~6°C) is too much for a ~2000-3000 gigatonne input of carbon [Higgins & Schrag, 2006; Pagani et al., 2006; Archer, 2007].

"…stratigraphic relationships … suggest that warming preceded (in part) massive input of carbon during the LPTM. Thus, addition of carbon cannot explain all of the inferred warming…"

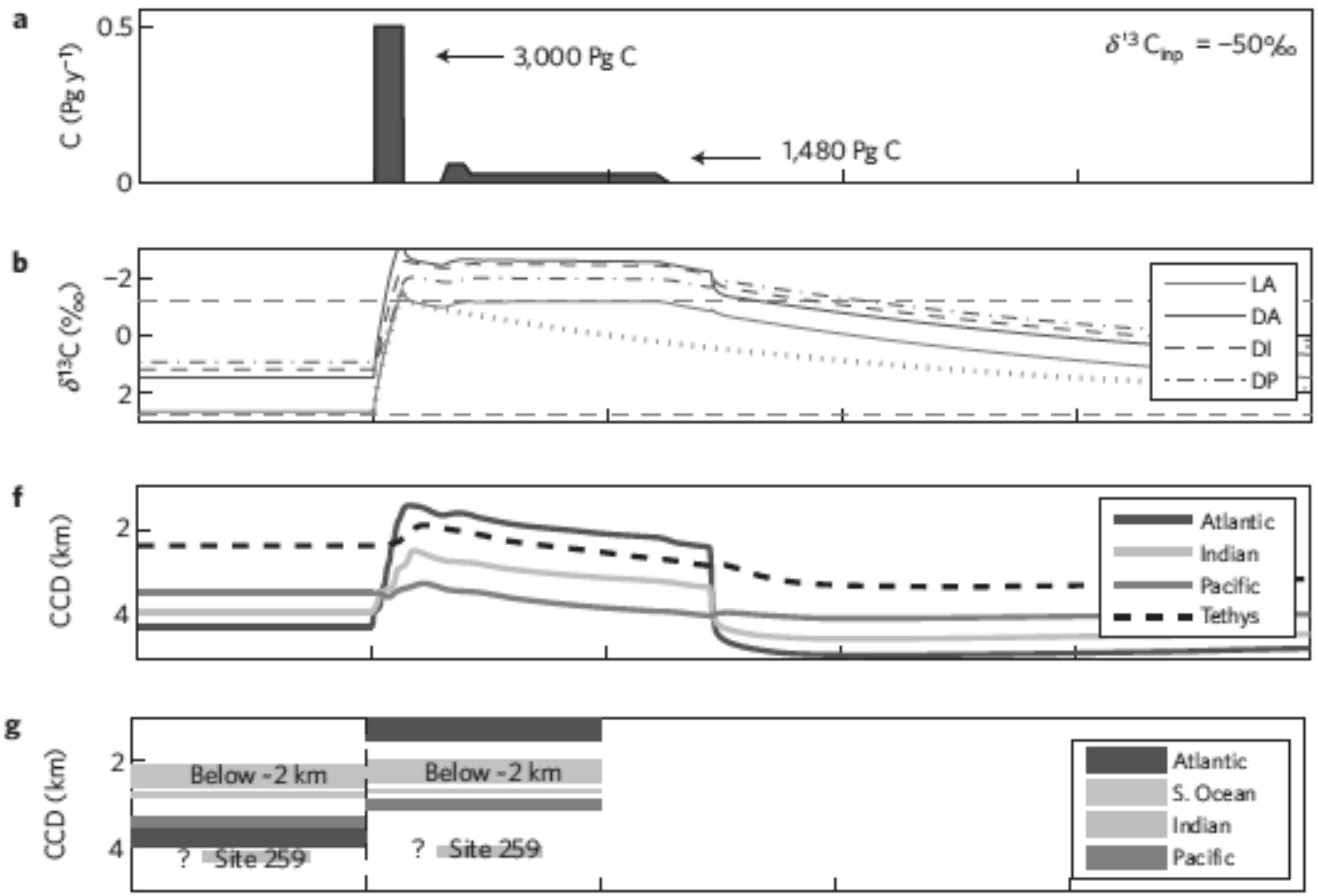
– Dickens et al., 1997

2. Carbonate dissolution across the PETM is too great for a ~2000-3000 Gt input of carbon [Zachos et al., 2005; Higgins & Schrag, 2006; Pagani et al., 2006; Archer, 2007] (based upon records at Walvis Ridge, Atlantic).

"Release of CH_4 from continental margin gas hydrate deposits and oxidation of a substantial fraction of this methane is a satisfactory explanation for several explanations that are difficult to explain by other mechanisms. These include: … dissolution of carbonate in pelagic sediment that is most pronounced in the Atlantic."

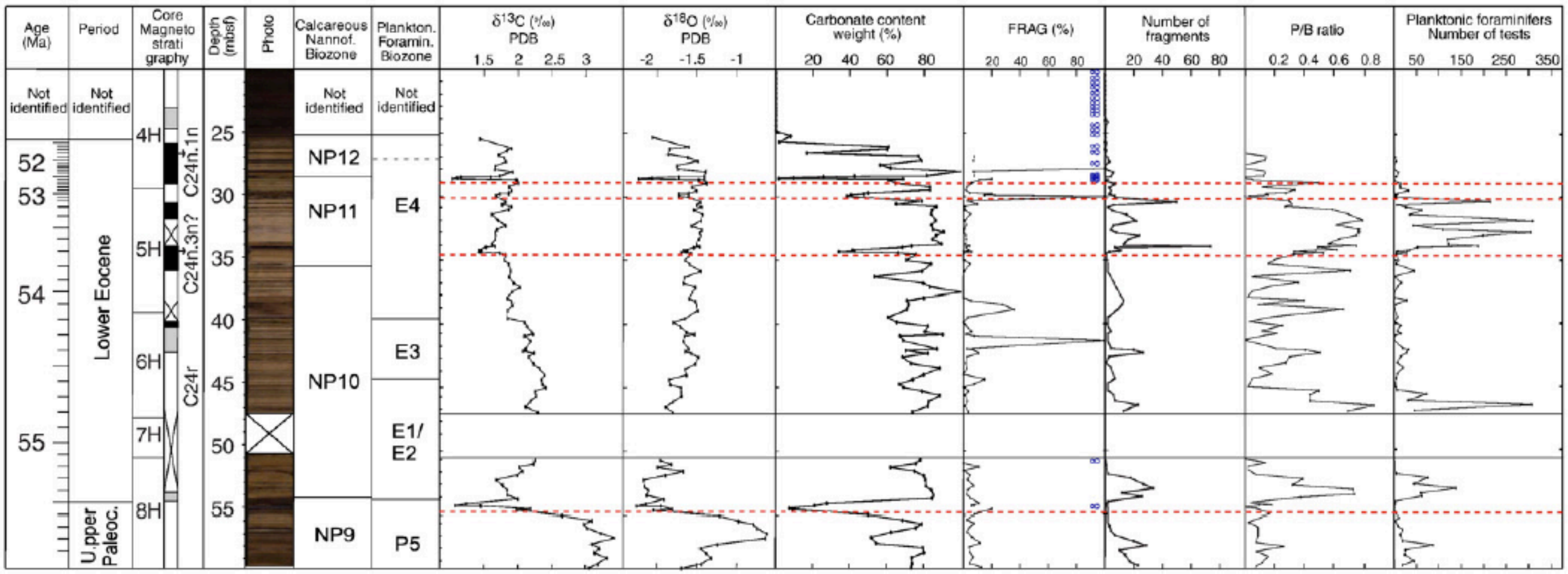
– Dickens, 2000

Carbonate dissolution across the PETM is too great for a ~2000-3000 gigatonne input of carbon



Zeebe et al., Nat. Geoscience, 2008

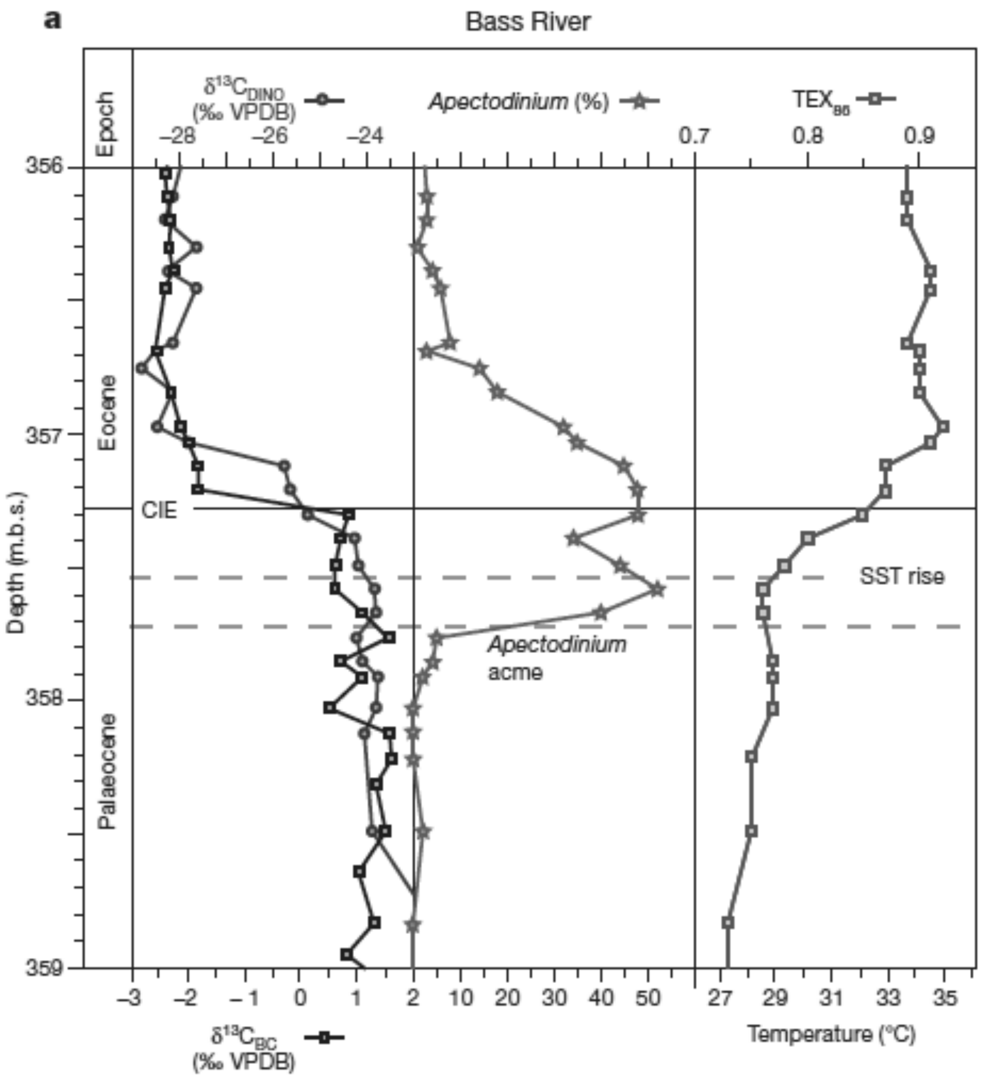
Site 1215, Equatorial Pacific



Leon-Rodriguez and Dickens, P³, 2010

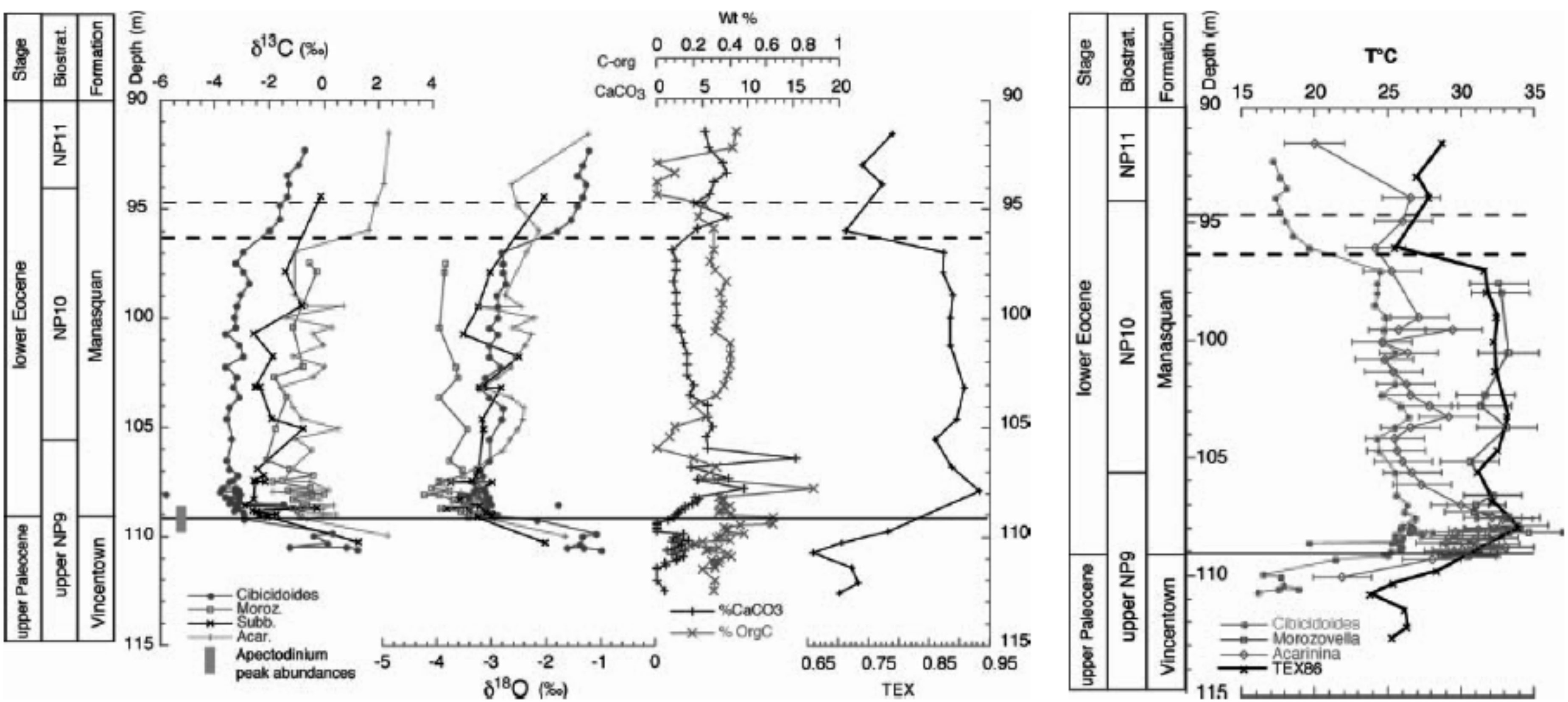
3. The $\delta^{13}C$ excursion across the PETM is much greater than 3‰ [Pagani et al., 2006a,b; Archer, 2007; blah, blah and blah …]

The $\delta^{13}C$ excursion across the PETM is much greater than 3‰



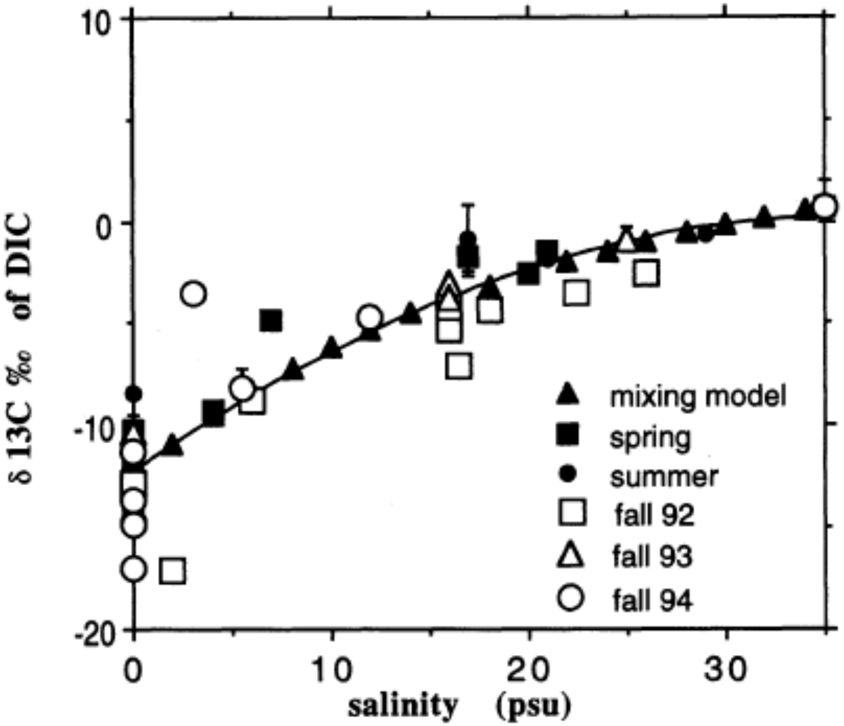
Sluijs et al., Nature, 2007

Stable Isotope Records at Bass River, New Jersey

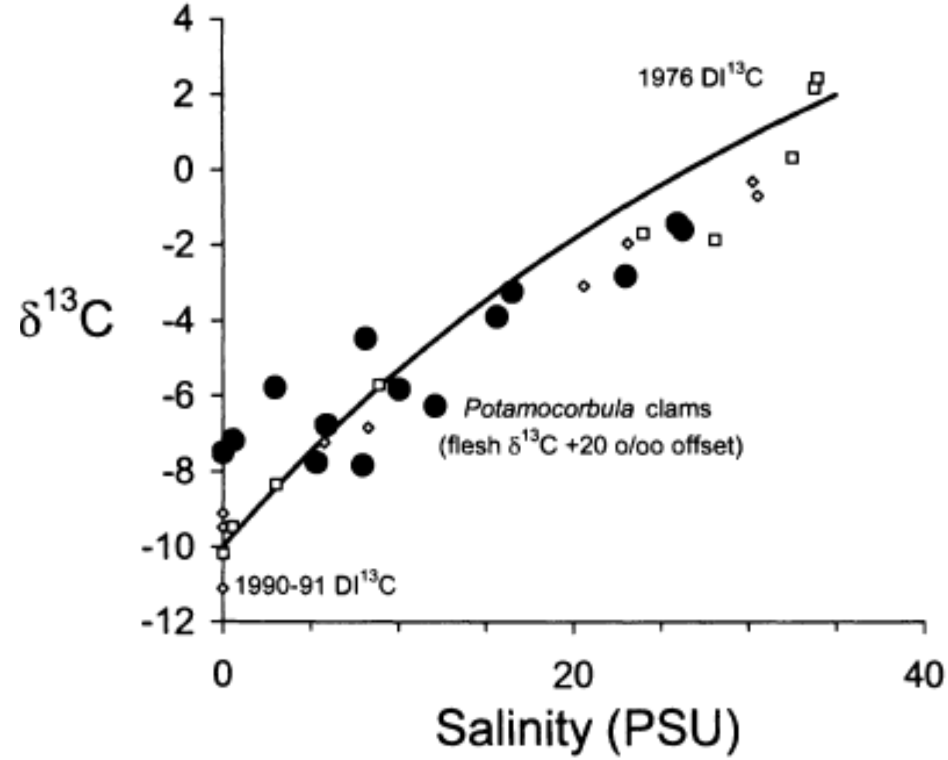


Zachos et al., Geology, 2006

Salinity and Carbon Isotopes

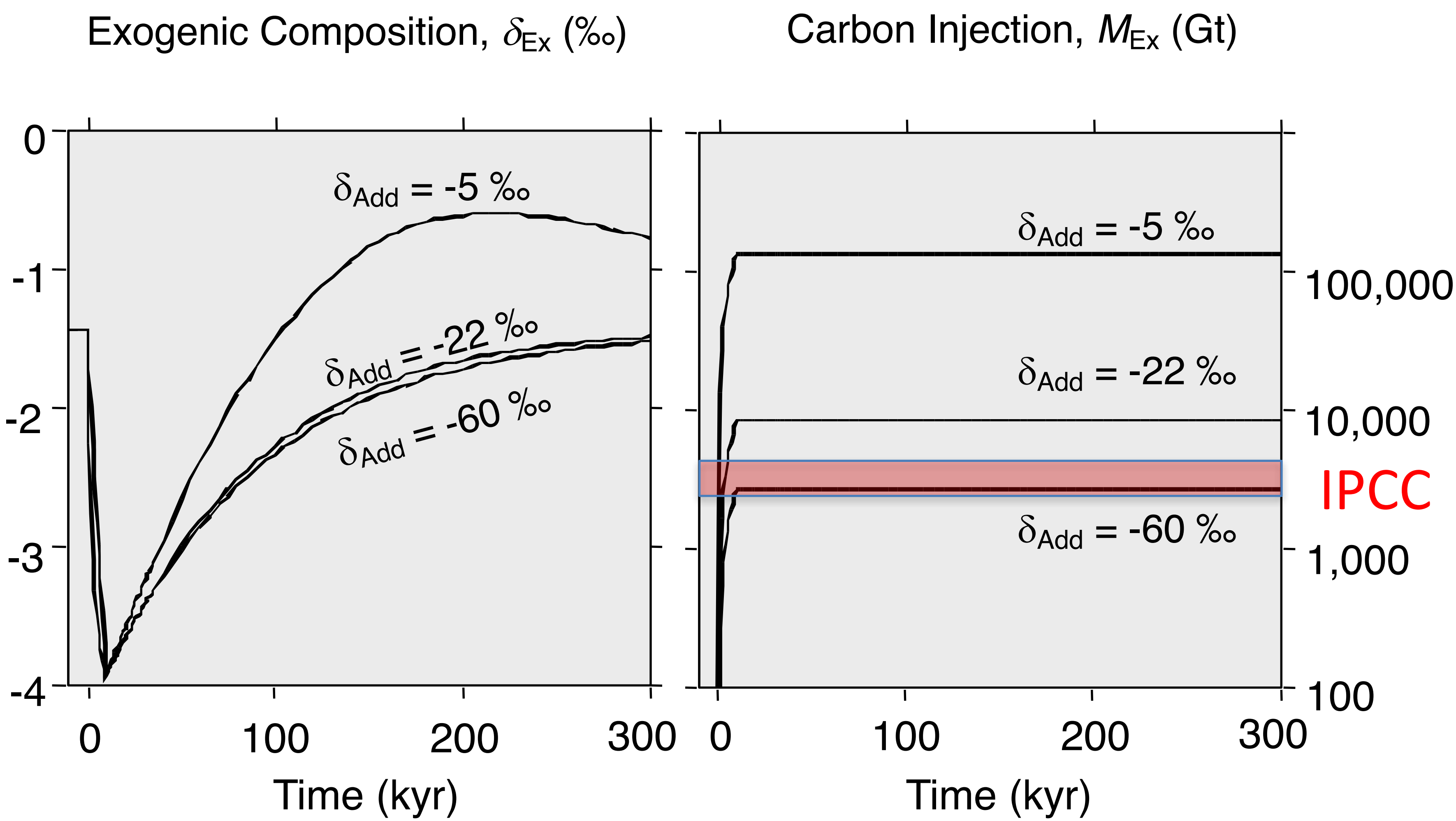


Chanton and Lewis, Estuaries, 1999



Fry, Estuaries, 2002

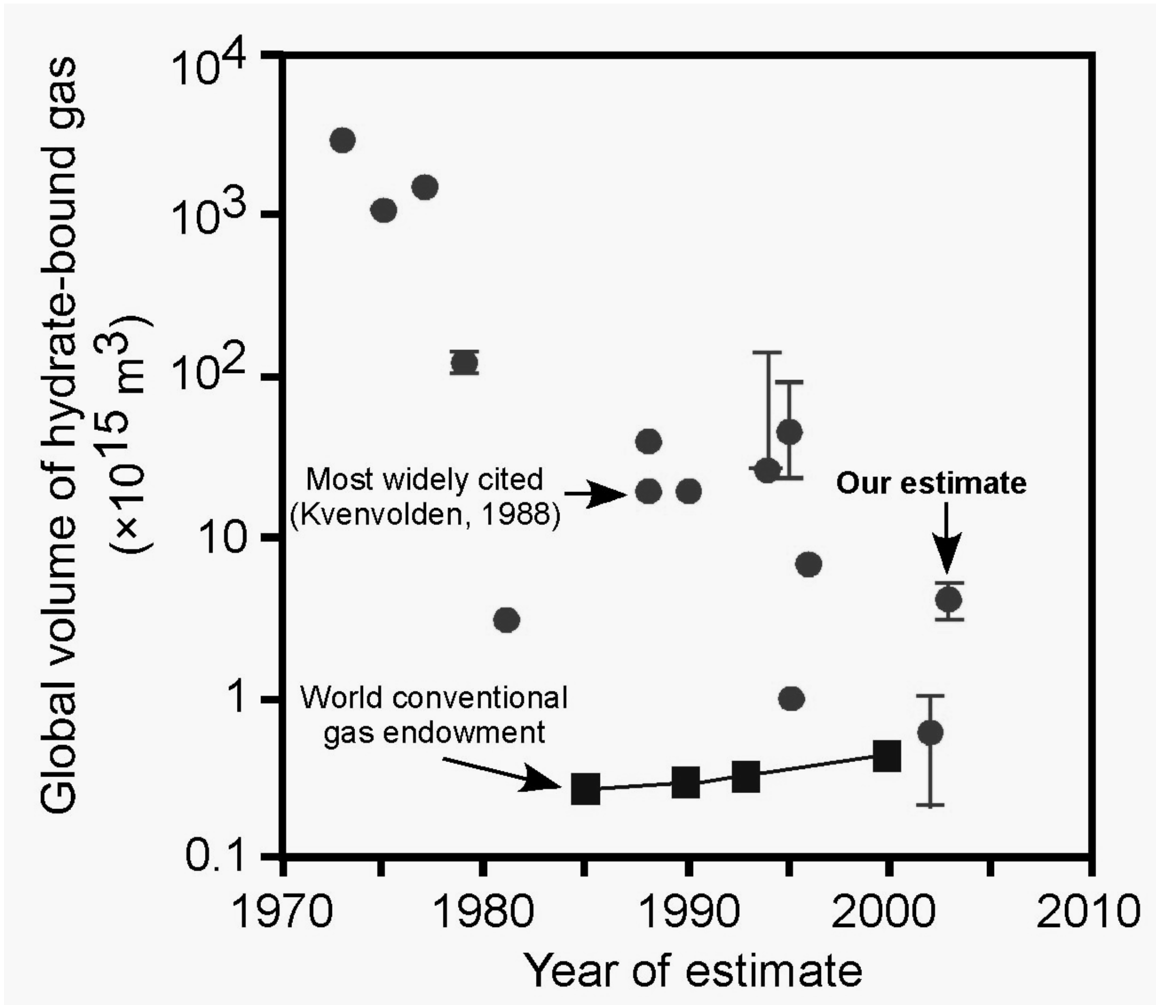
Theoretical Carbon Inputs for Rapid, Global, Negative $\delta^{13}C$ Excursions



Dickens, Geol. Soc. London, 2001

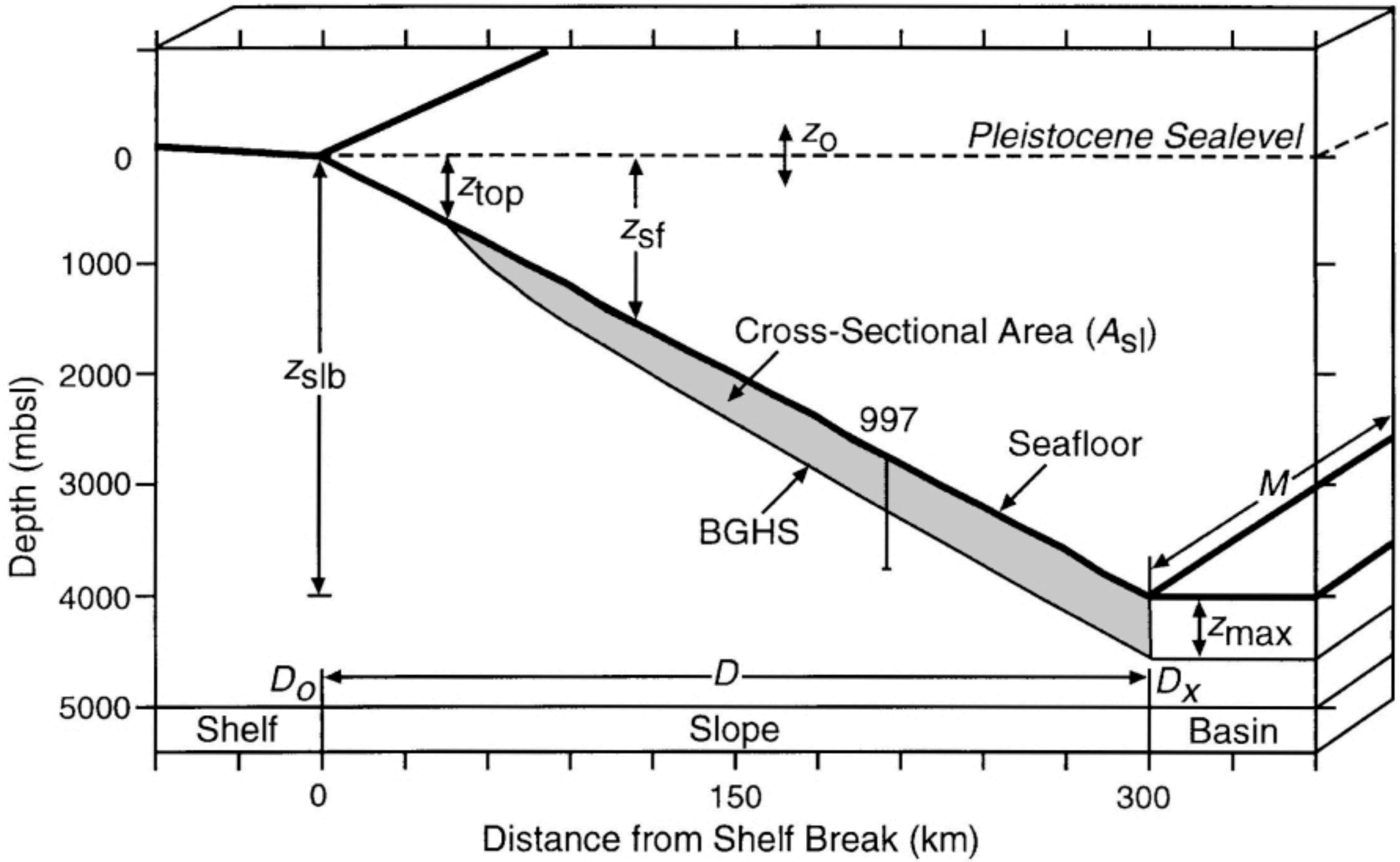
11. Modern Gas Hydrate Distribution

Global Gas Hydrate Estimates – Modern Day



Milkov, Earth Sci. Rev, 2004

Potential Volume of Gas Hydrate



Dickens, Organic Geochemistry, 2001

Milkov's Estimate: 500 - 2500 Gigatonnes

Total Potential Volume on Slopes: 7×10^6 km^3

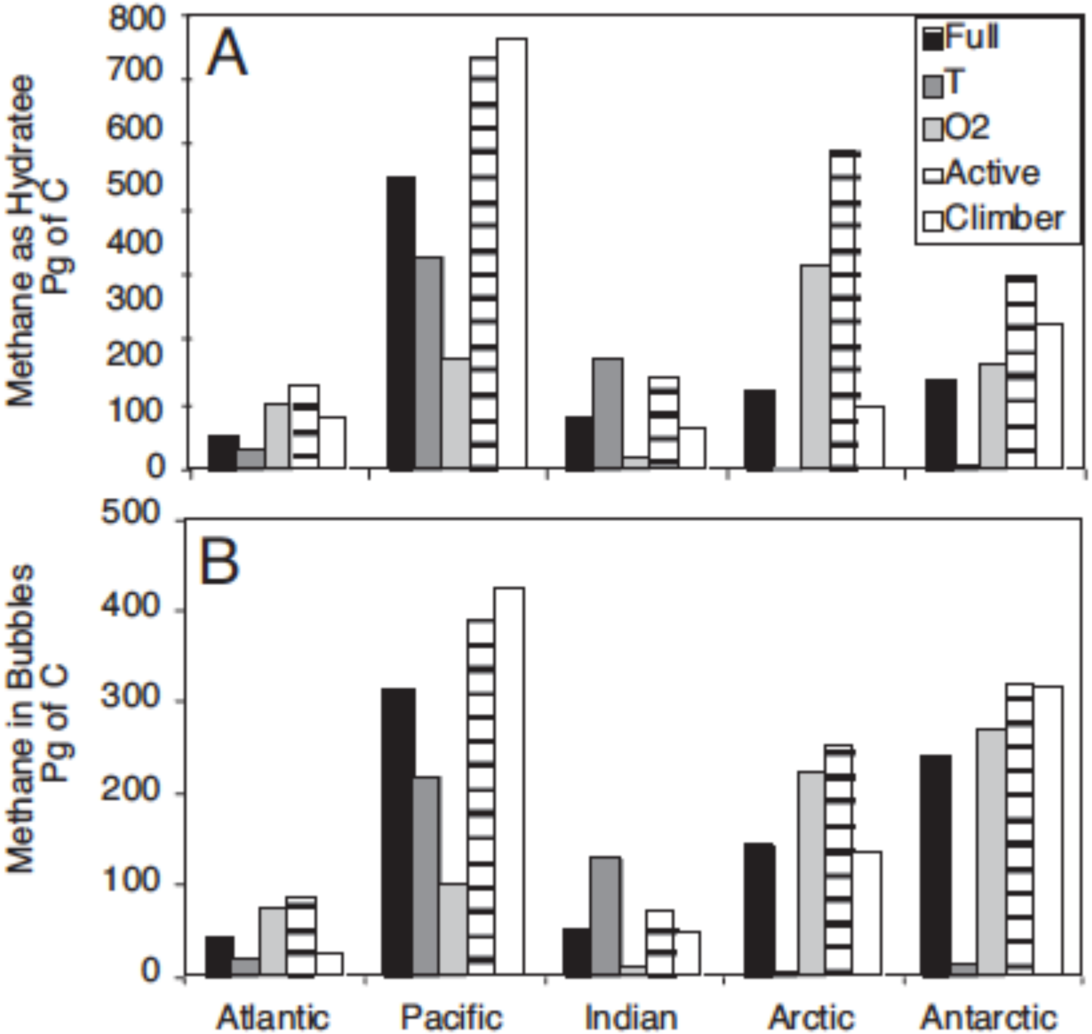
Percentage with Gas Hydrate: 10 - 30%

Average Gas Hydrate: 0.7 – 1.2% (by volume)

HOWEVER:
Leads to only 0.5 – 1.6% of seafloor with gas hydrate!

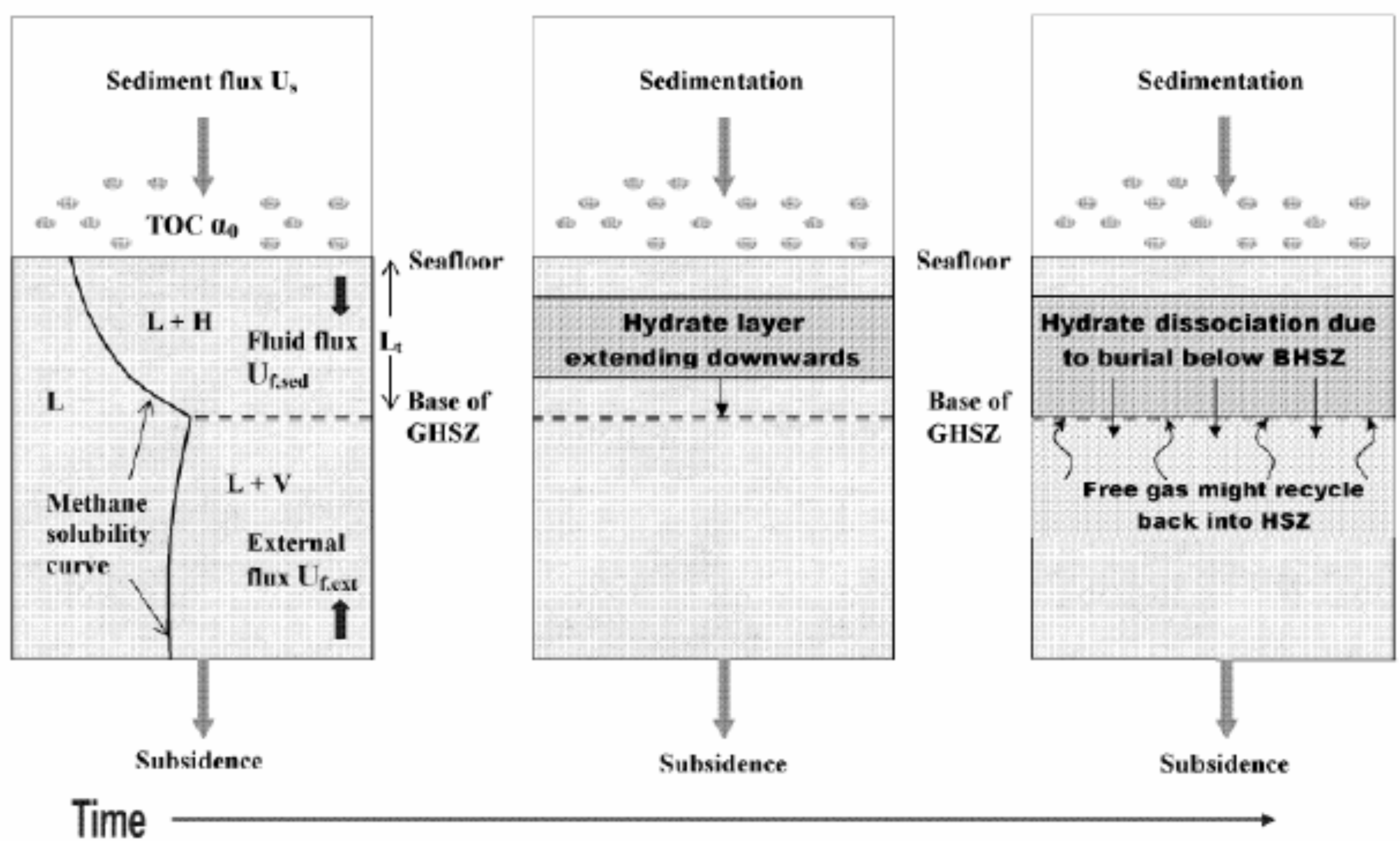
And where drilled often 1-3 % by volume

Archer's Estimate: ~2000 Gigatonnes



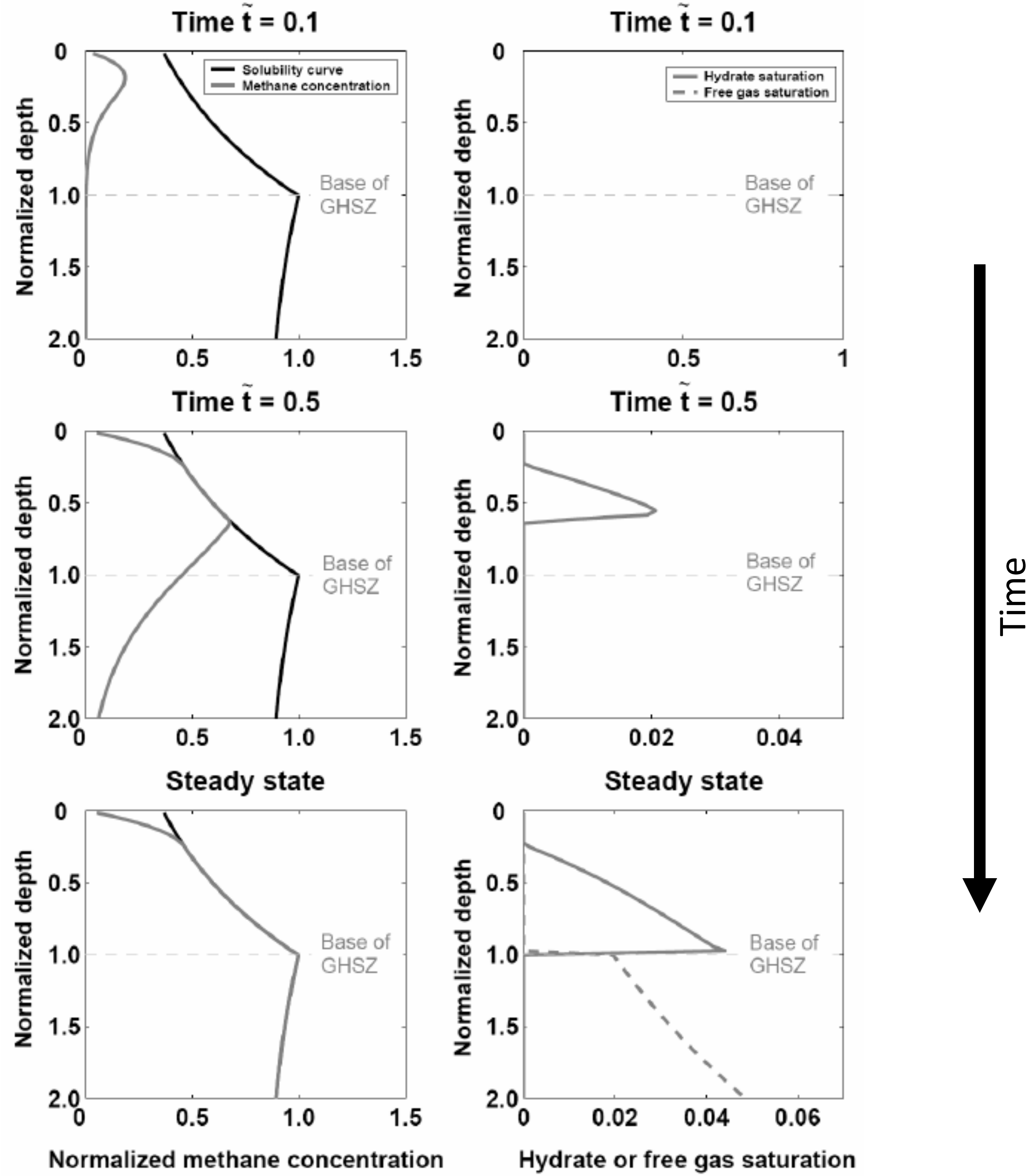
Archer et al., PNAS, 2009

Model Framework (1-dimensional)



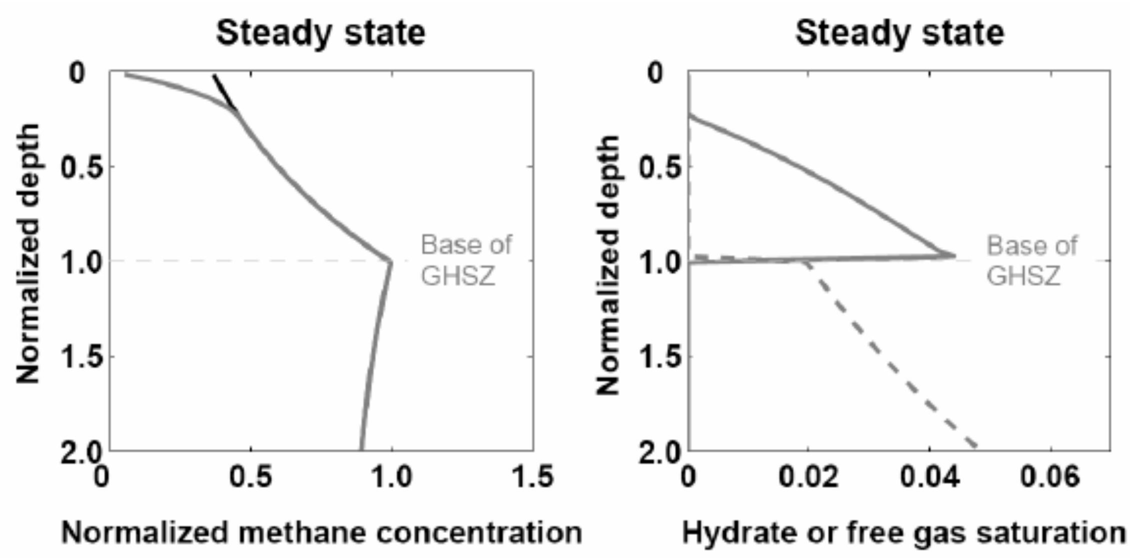
Bhatnager et al., Am. J. Sci., 2007

General Model for Gas Hydrate Accumulation

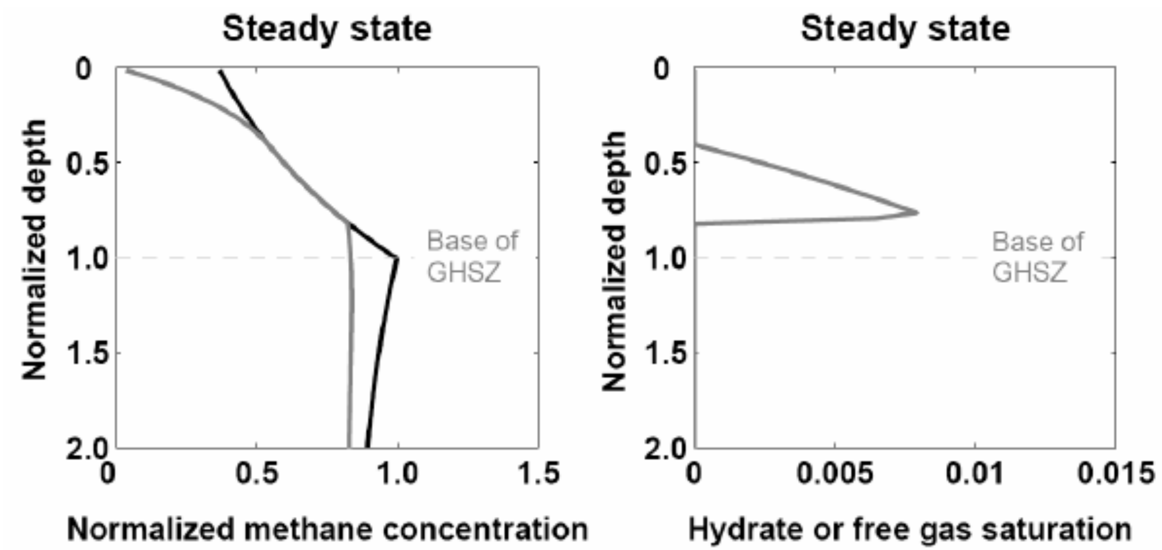


Bhatnager et al., Am. J. Sci., 2007

Effect of Organic Carbon Input



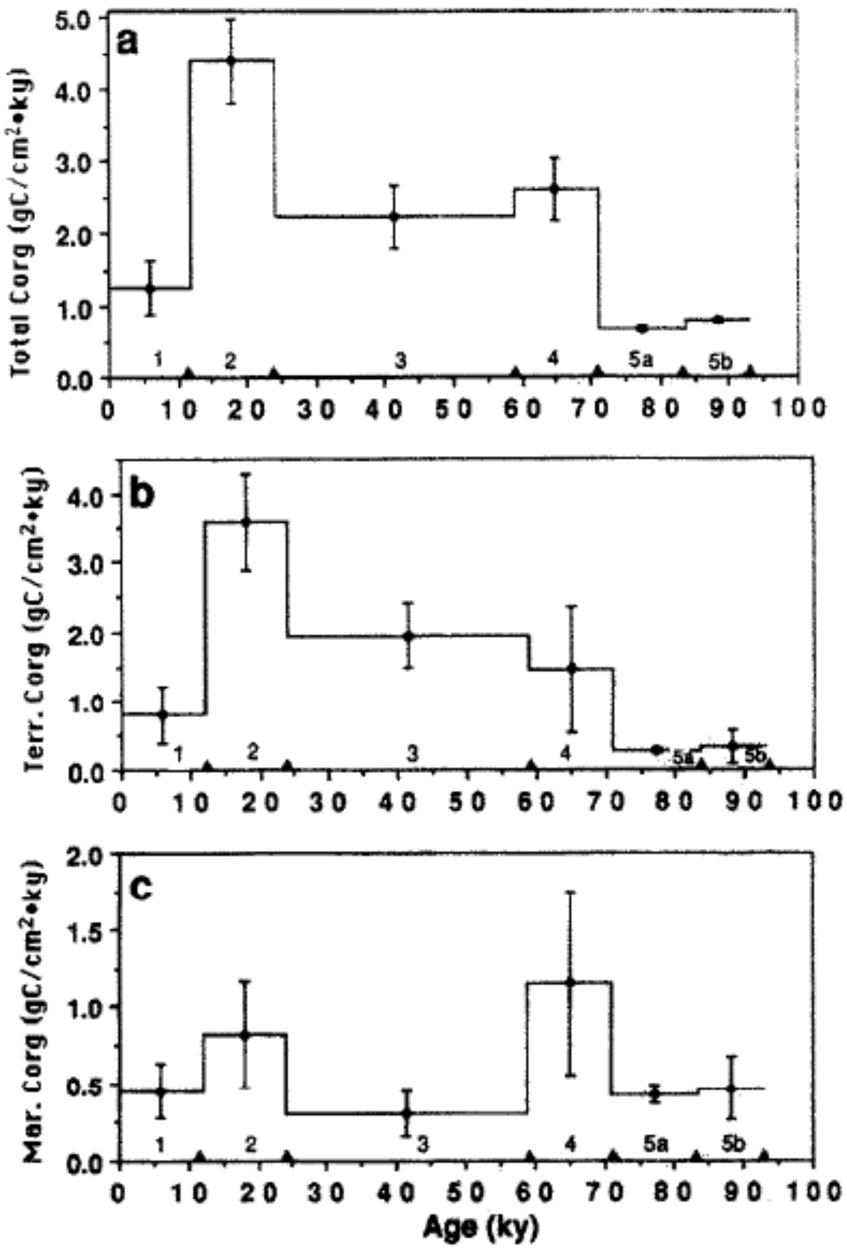
β --> high



β = normalized organic input

β --> moderate

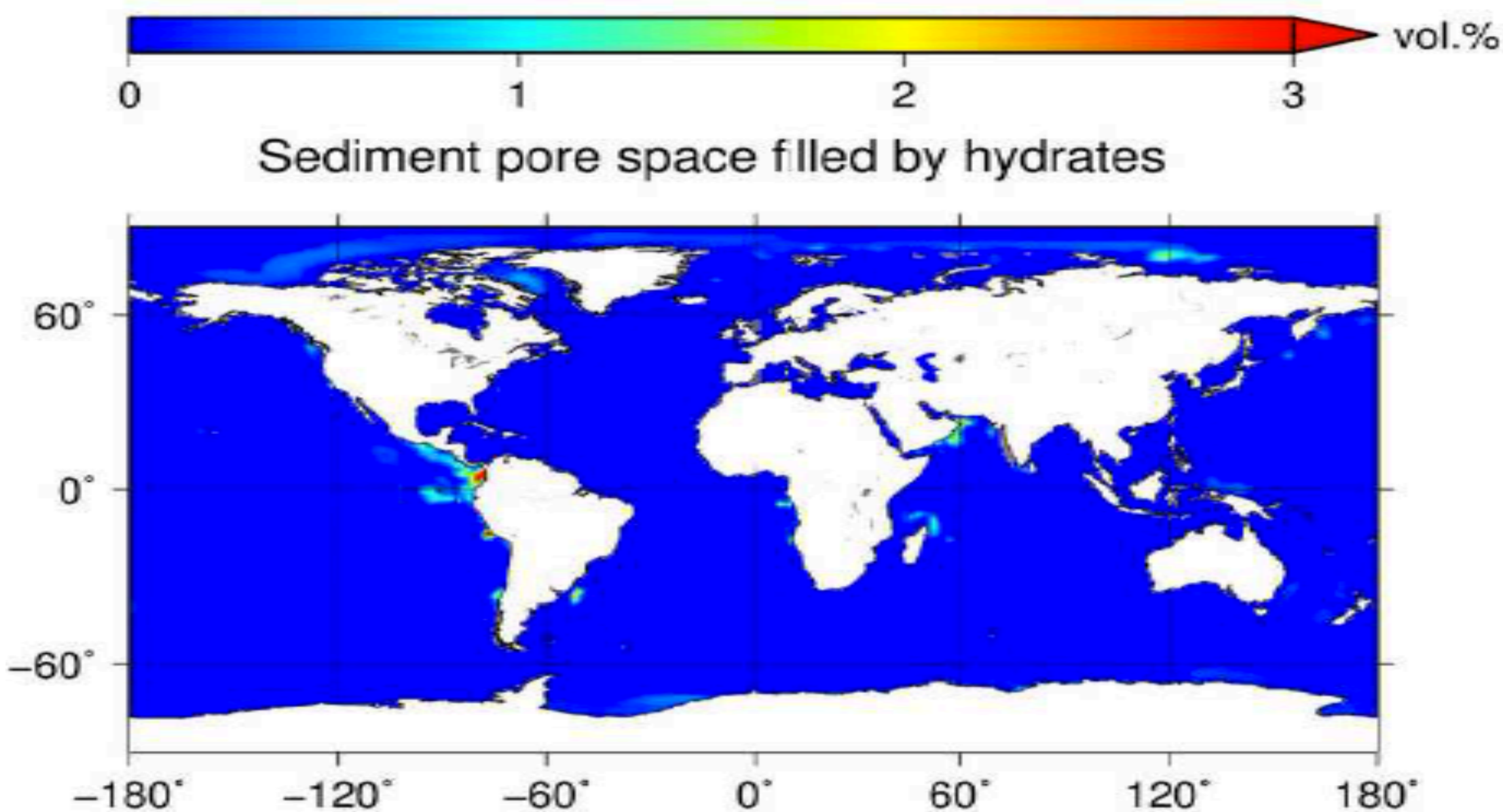
Bhatnager et al., Am. J. Sci., 2007



Organic Carbon Input To Continental Slopes

Jasper & Gagosian, GCA, 1990

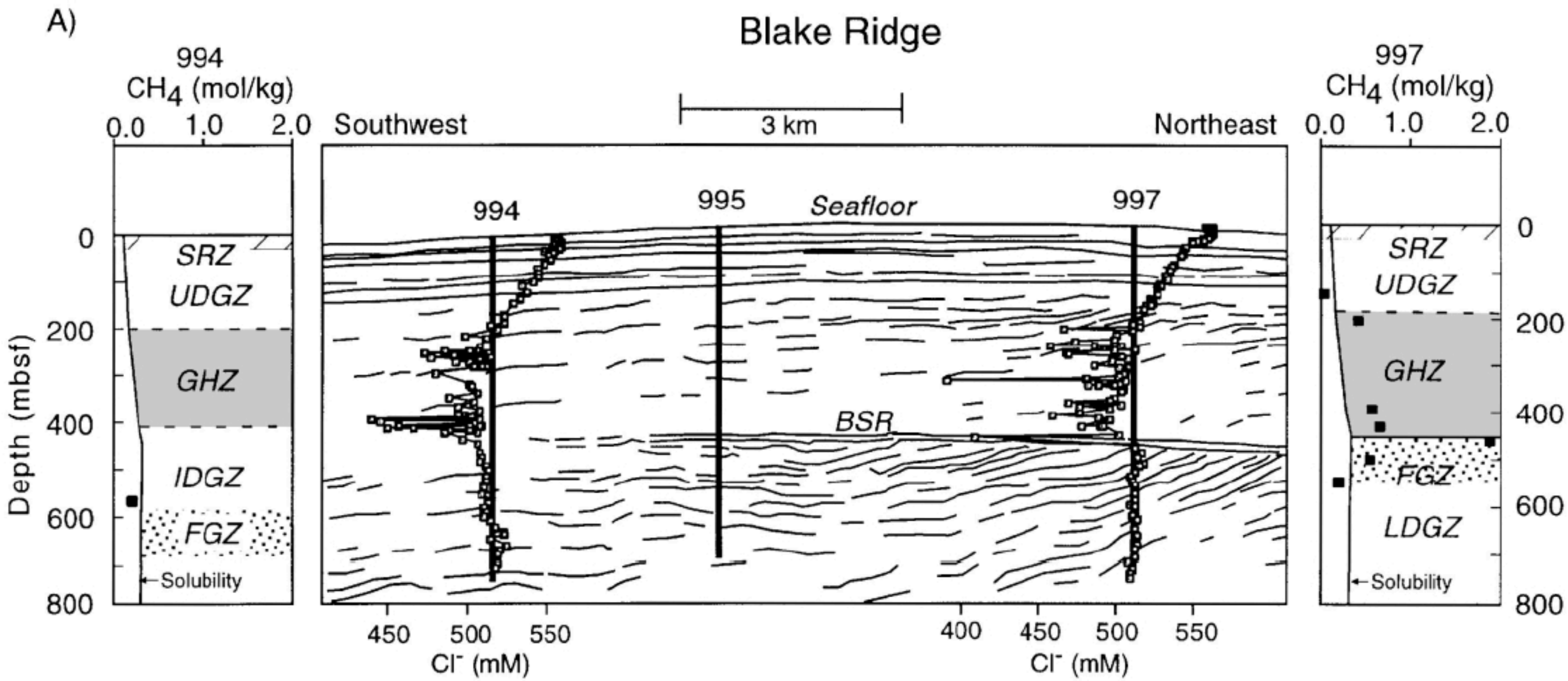
Modeled Gas Hydrate on Continental Slopes



Burwicz's (Wallmann's) Estimate: < 800 Gt

Burwicz et al, GCA, 2011

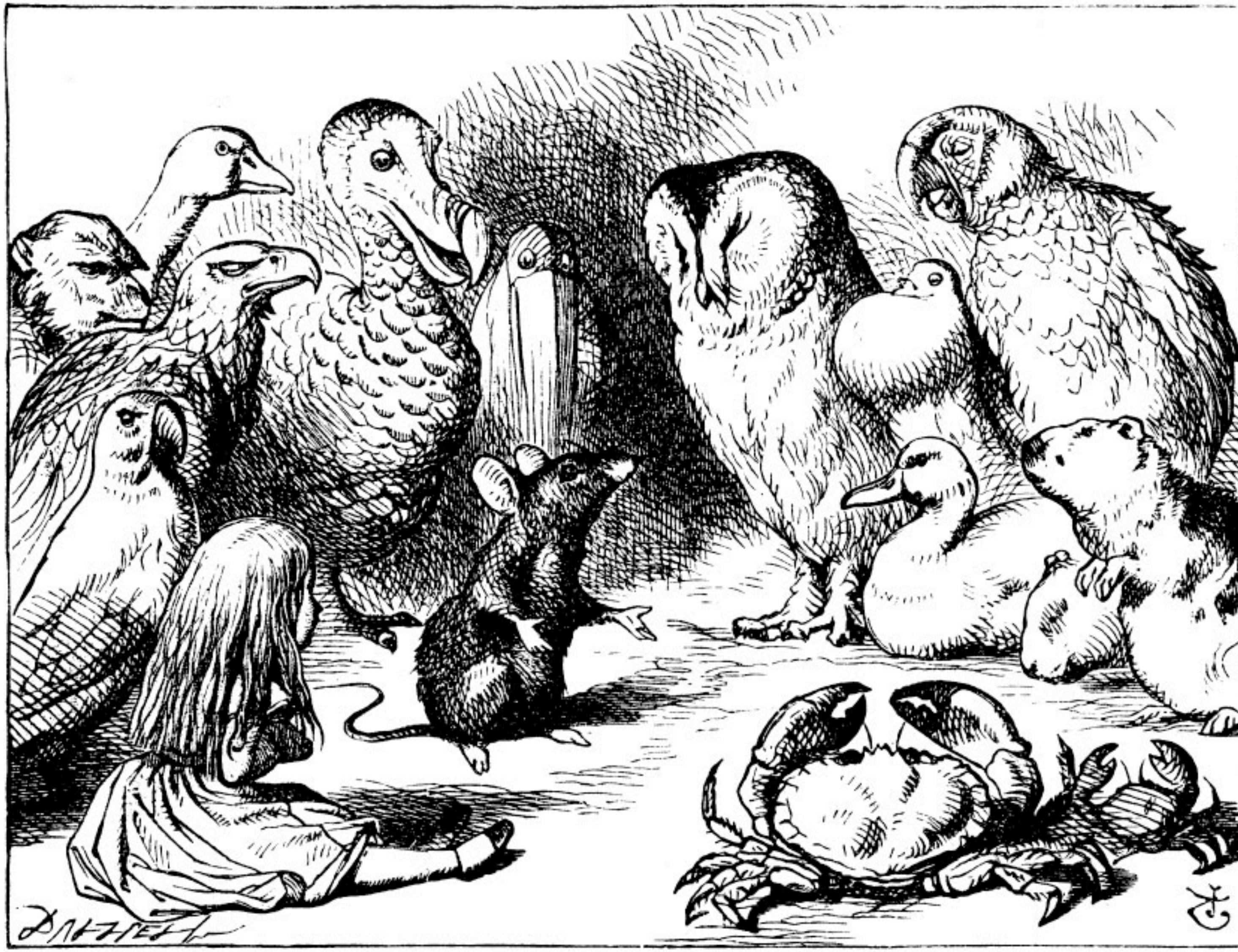
Blake Ridge: A fairly well-constrained gas hydrate system



~ 4% of pore space

Dickens, Org. Geochemistry, 2001

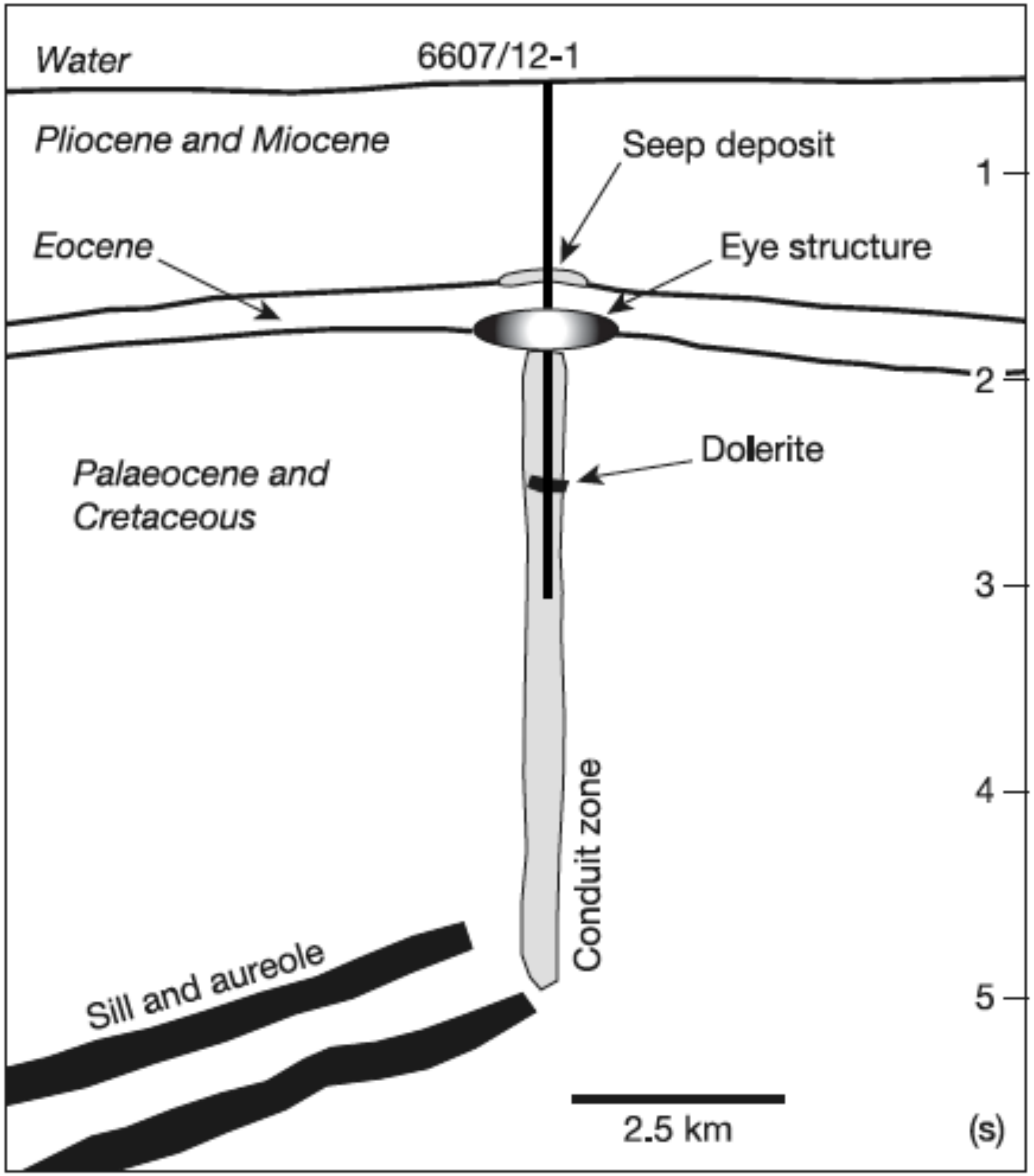
12. Other Hypotheses for Carbon Release



Impact of a Carbonaceous Comet
– Kent and Colleagues (EPSL, 2003)

Dessication of Epi-Continental Seas and Oxidation of Marine Organic Carbon
– Higgins & Schrag (EPSL, 2006)

Level 5: 1. What about volcanoes?



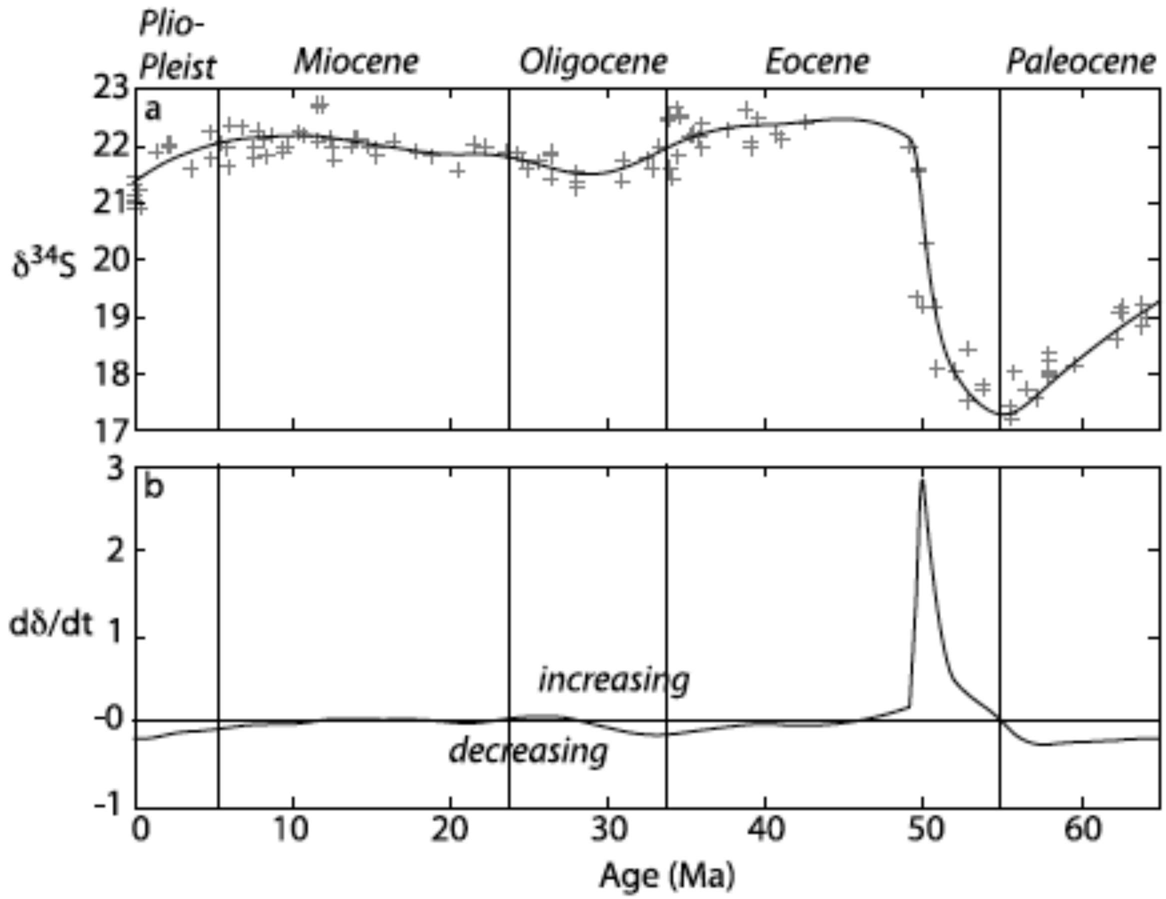
Burning of Peat

– *Kurtz and Colleagues (Paleoceanography, 2003)*

Oxidation of Permafrost

– *DeConto and colleagues (Nature, 2010)*

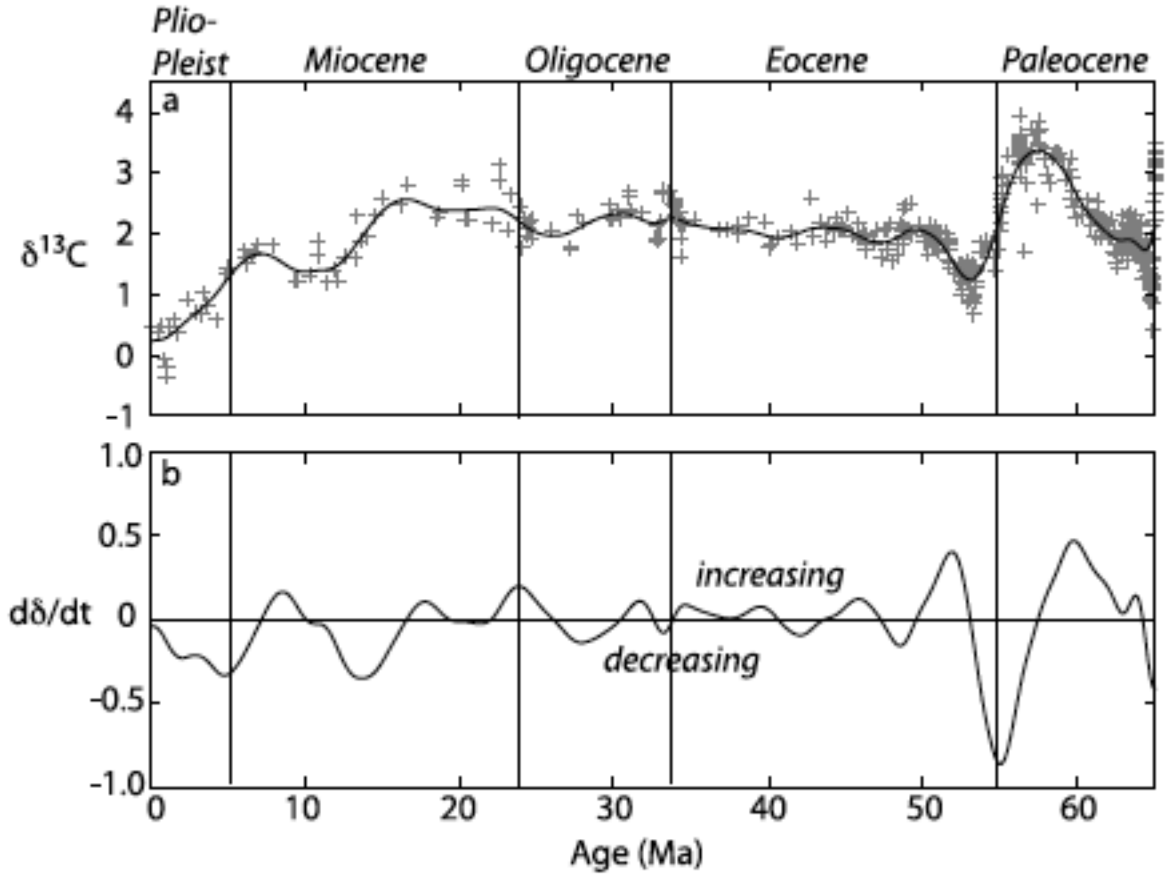
Fe Sulfides



Kurtz et al., Paleoceanography, 2003

Fe Sulfides

High C/Low S



Kurtz et al., Paleoceanography, 2003

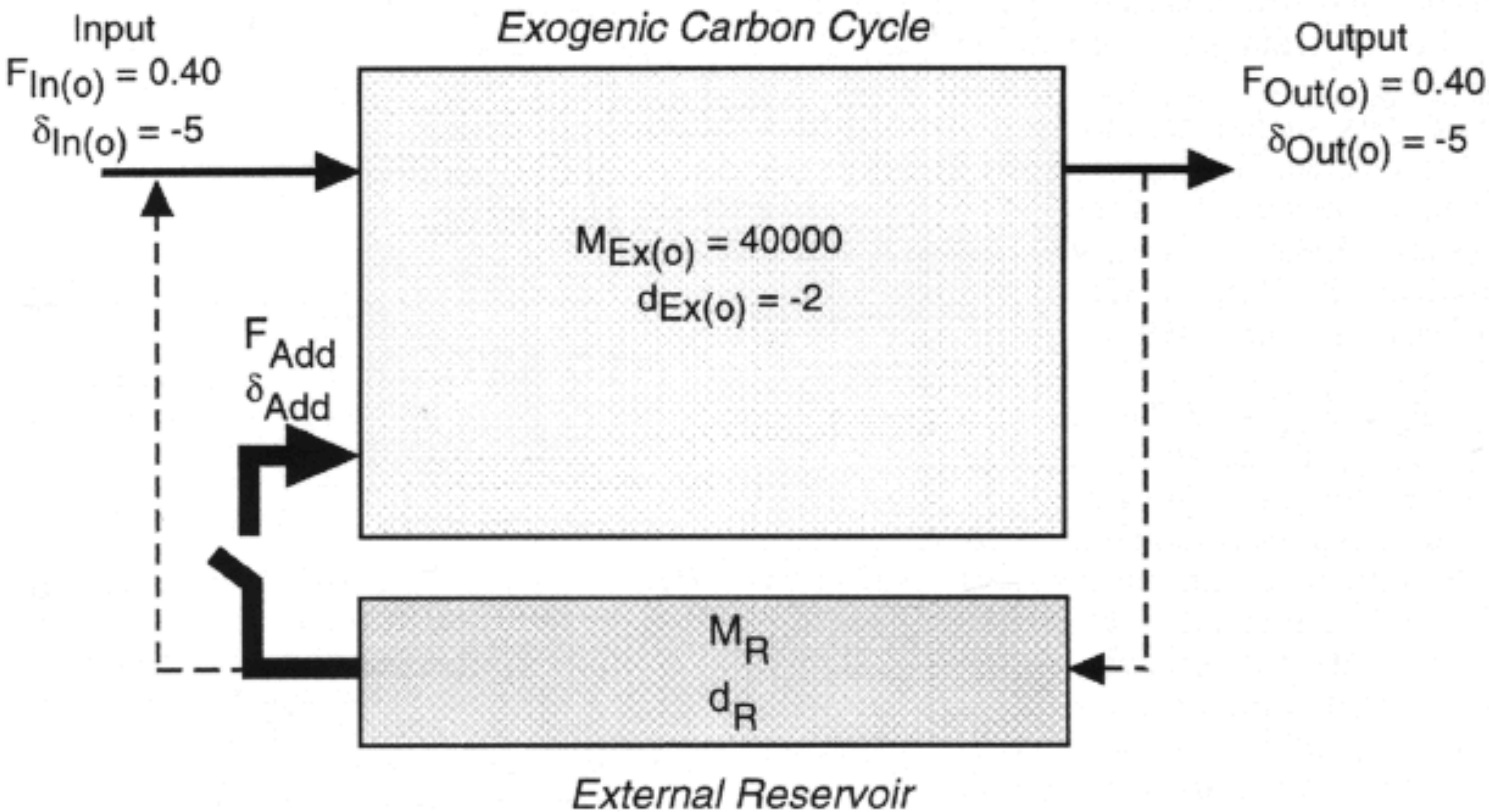
13. Summary and Progression

(A) *There are no good arguments against gas hydrate dissociation*

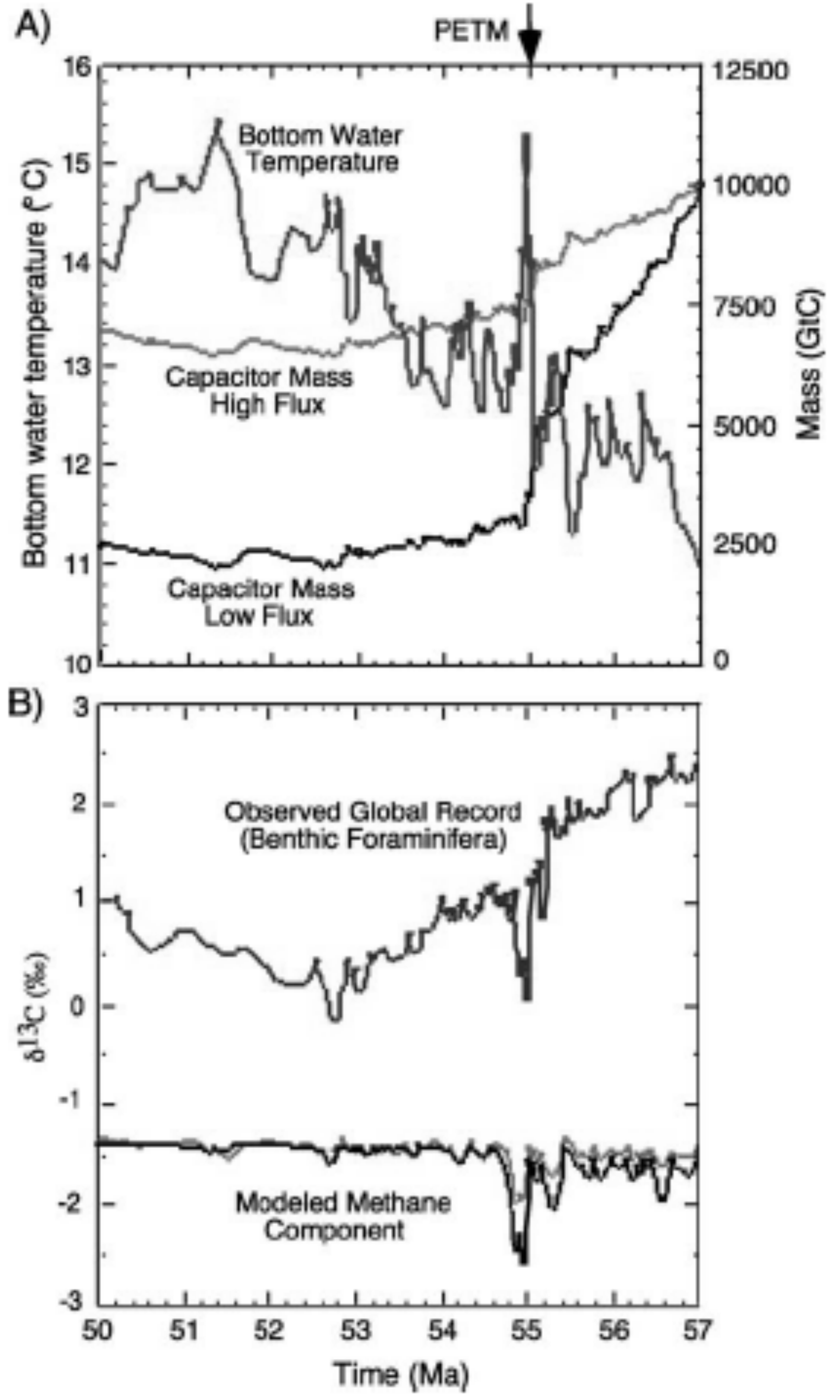
(B) *There are no better alternative explanations for the carbon input*

A Simple Model for a Global Carbon Isotope Excursion

Masses in Gigatonnes; Fluxes in Gt/yr; Delta in per mil

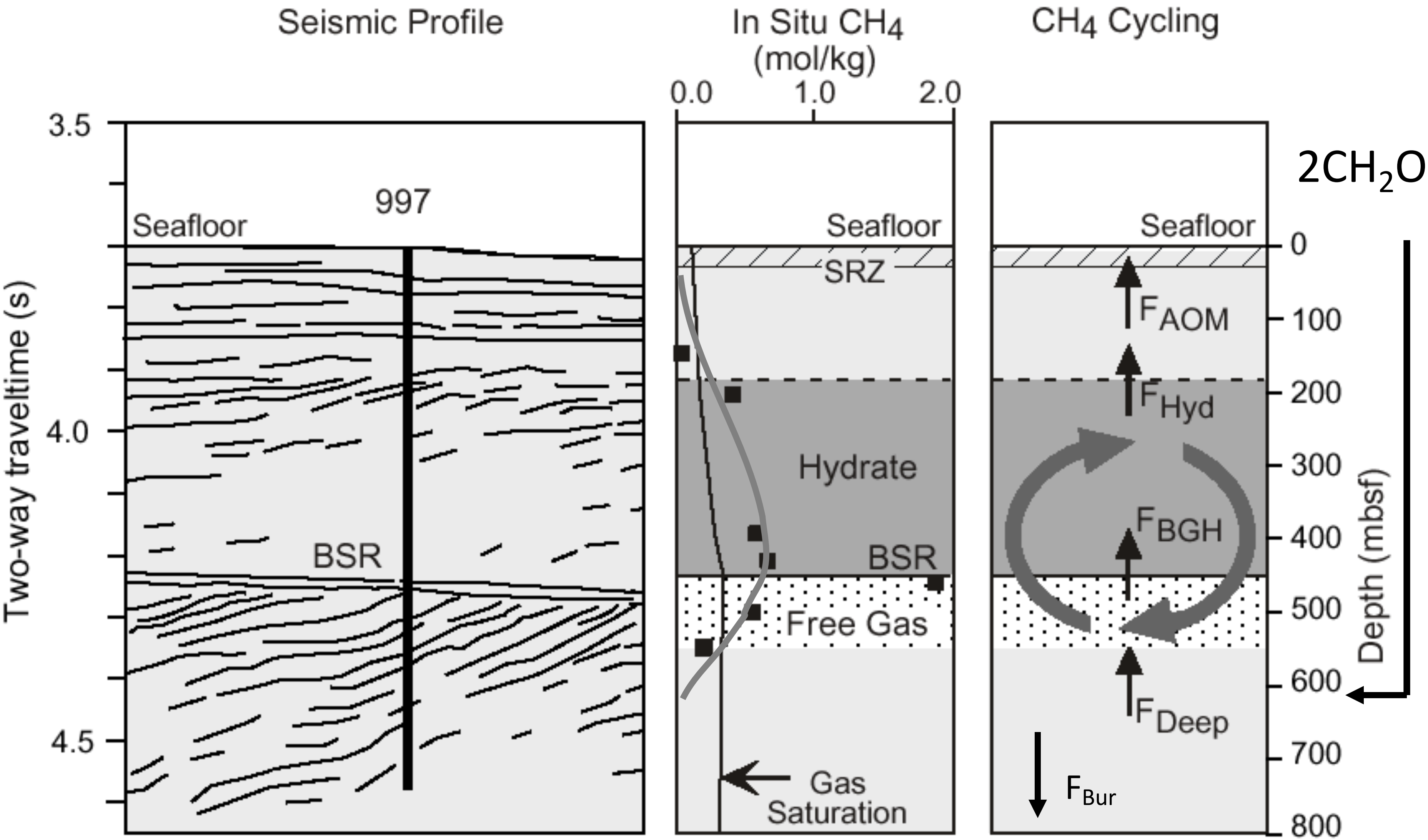


Dickens, Geol. Soc. London, 2001



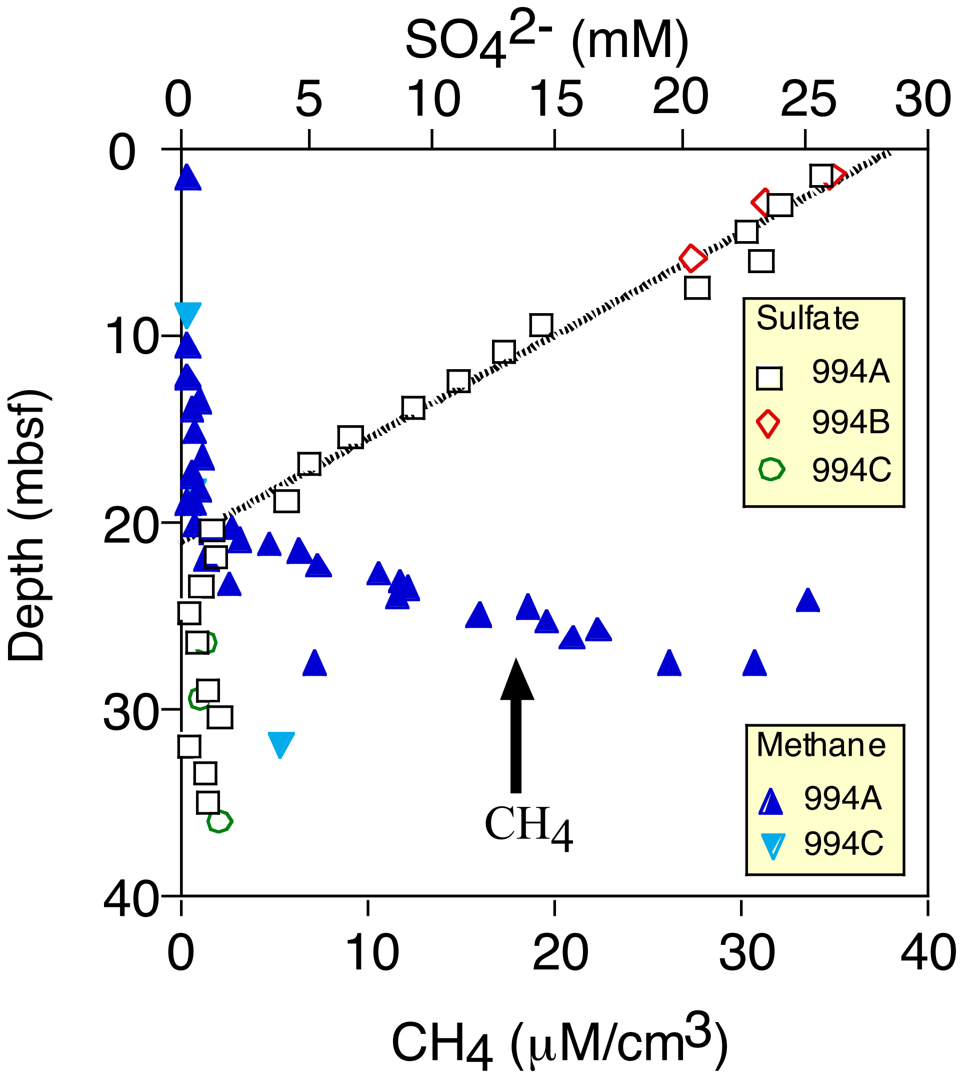
Dickens, EPSL, 2003

Methane and Theoretical Cycling: Blake Ridge, Site 997



Dickens, EPSL, 2003

Methane Loss: Blake Ridge ODP Site 994

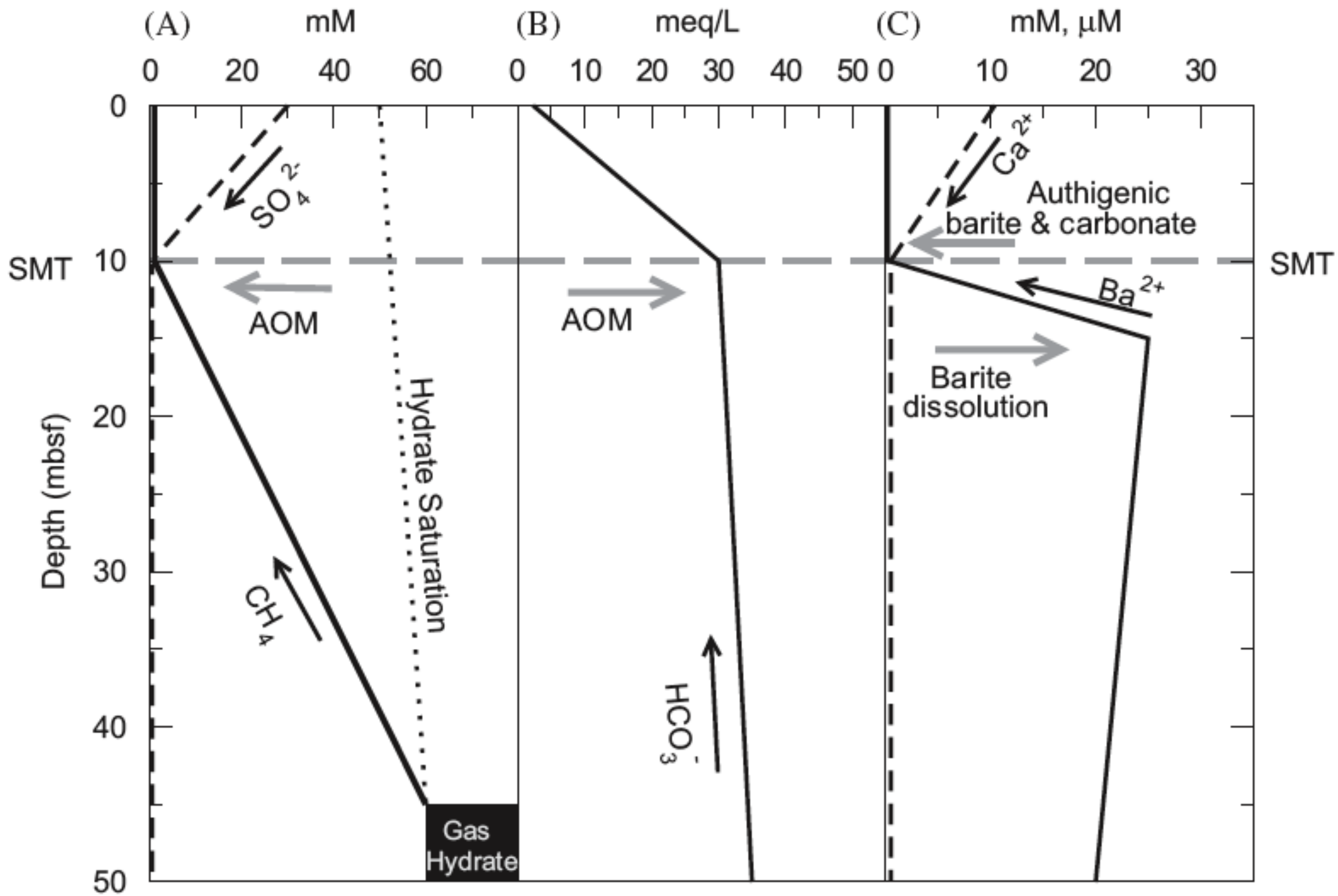


Anaerobic Oxidation of Methane (AOM)

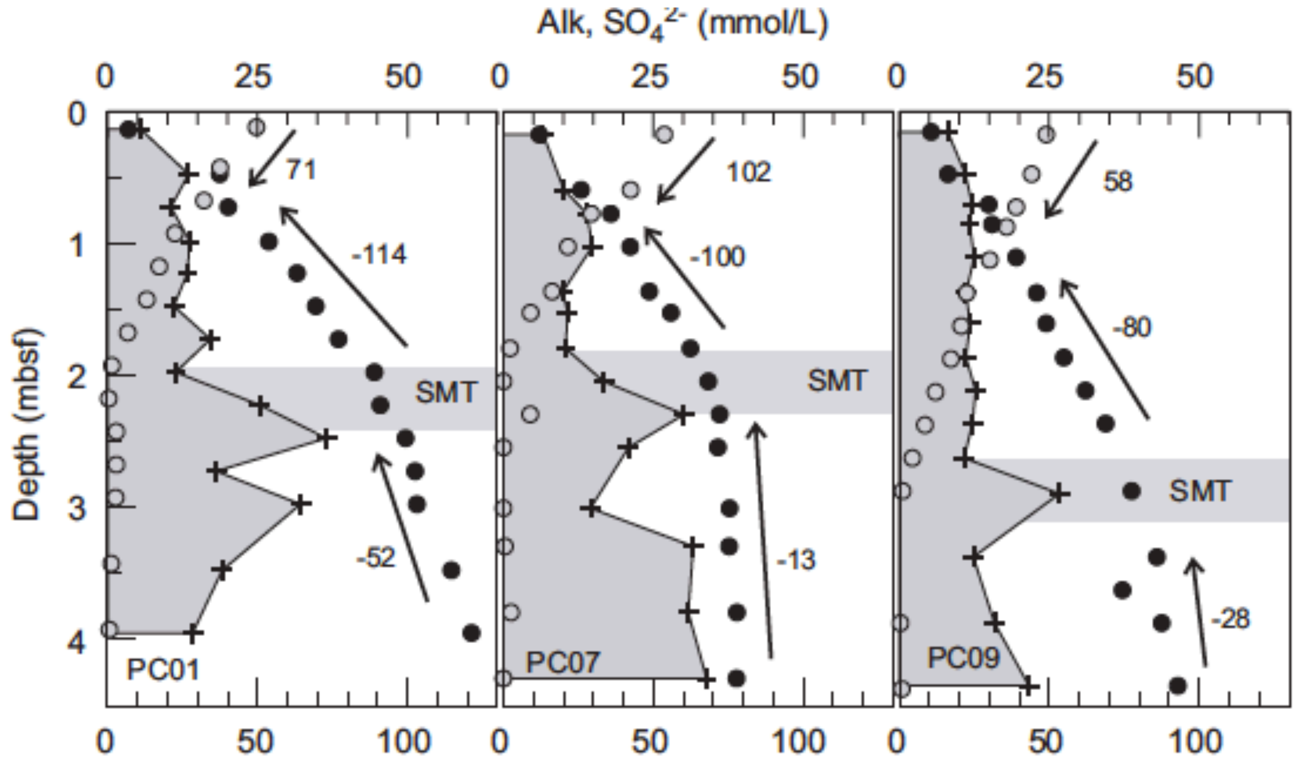
$$^{12}CH_4 + SO_4^{2-} \longrightarrow H^{12}CO_3^- + HS^- + H_2O$$

Paull et al., Proc. ODP, 1996; Borowski et al., Mar. Geology, 1999

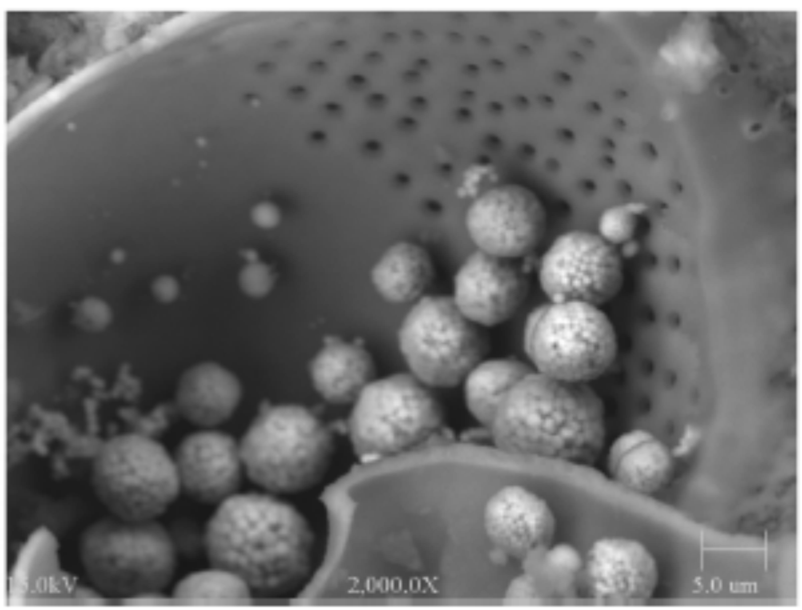
Gas Hydrate, AOM, Authigenic Minerals: The Link



Snyder et al., Deep-Sea Res., 2007



(B)

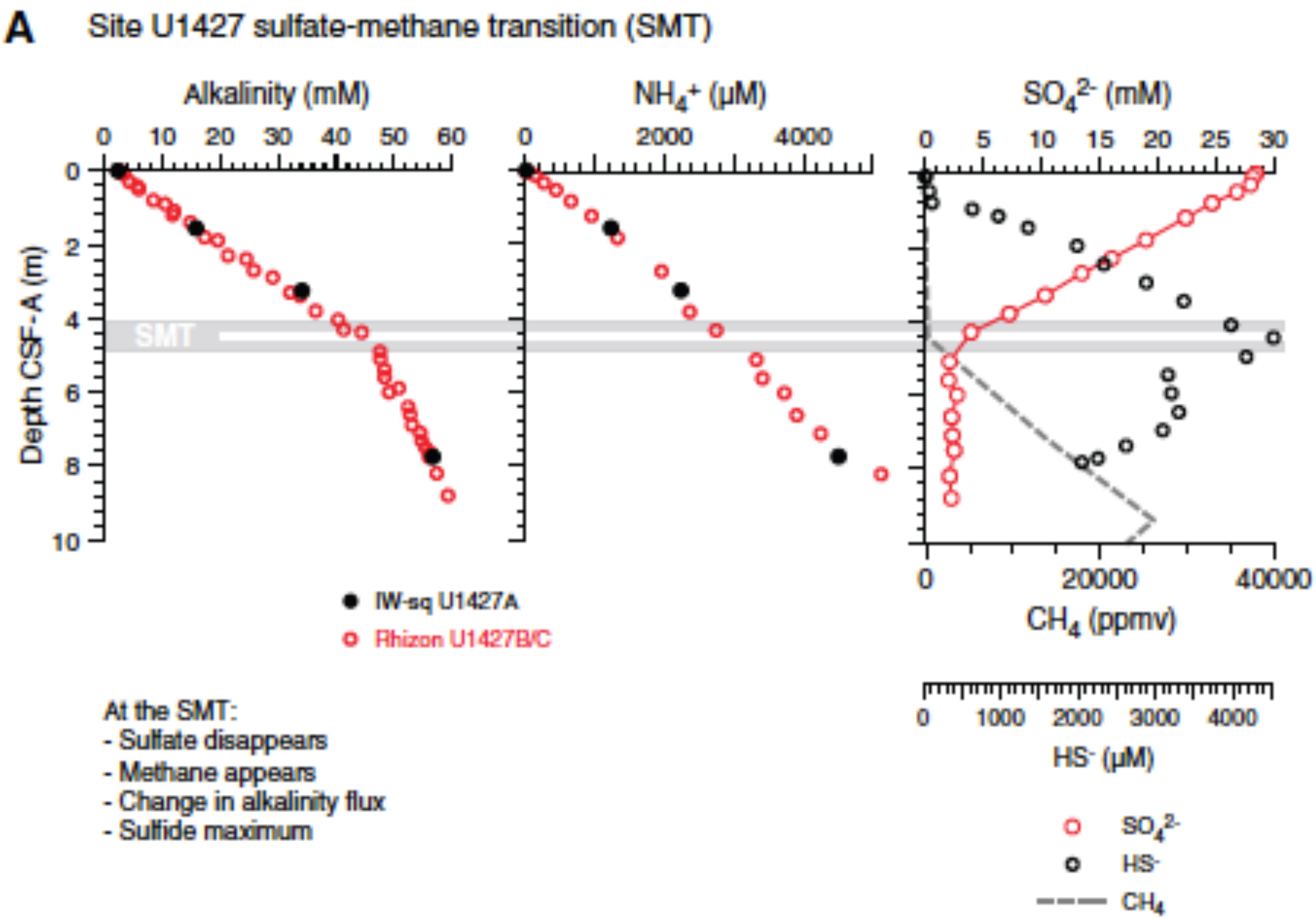


● Alkinity (HCO3-)

○ SO_4^{2-}

✚ Solid S

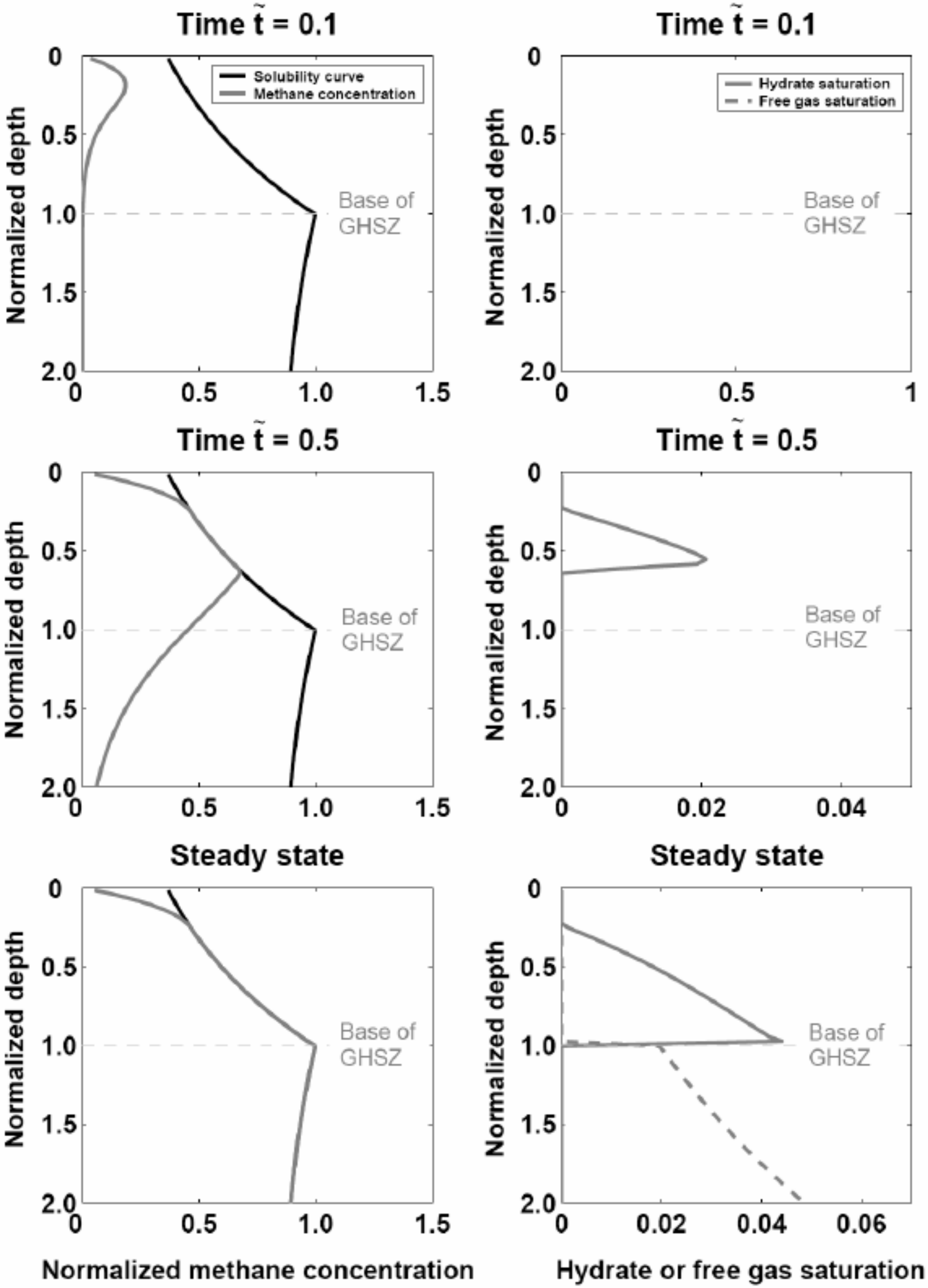
Snyder et al., Deep-Sea Res., 2007

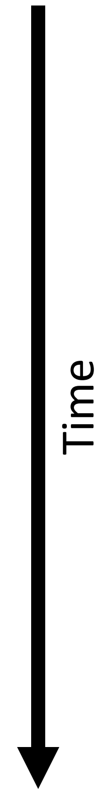


At the SMT:
- Sulfate disappears
- Methane appears
- Change in alkalinity flux
- Sulfide maximum

[*Expedition 346 Scientists, 2014*]

General Model for Gas Hydrate Accumulation

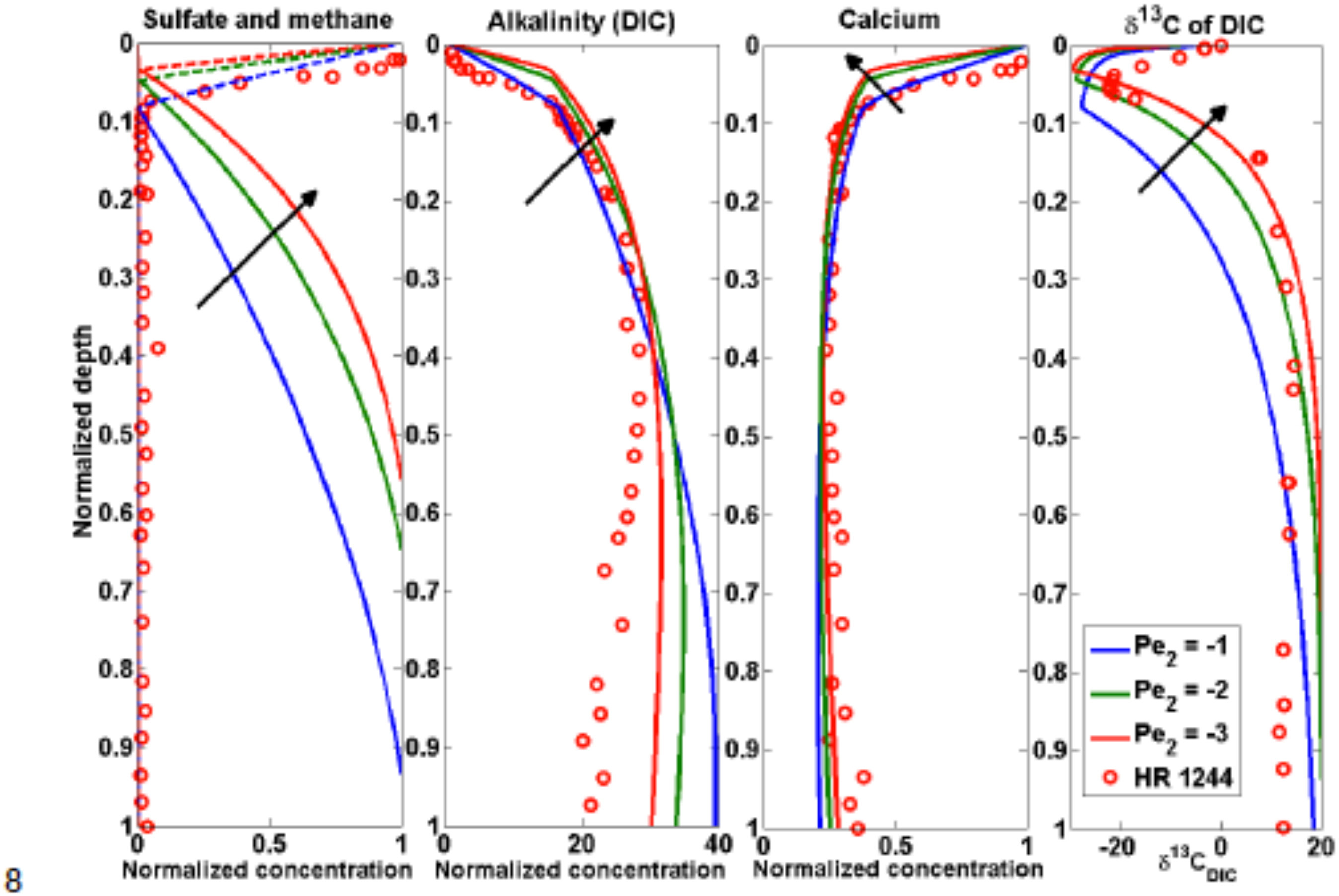




$$2CH_2O \dashrightarrow {}^{12}CH_4 + {}^{13}CO_2$$

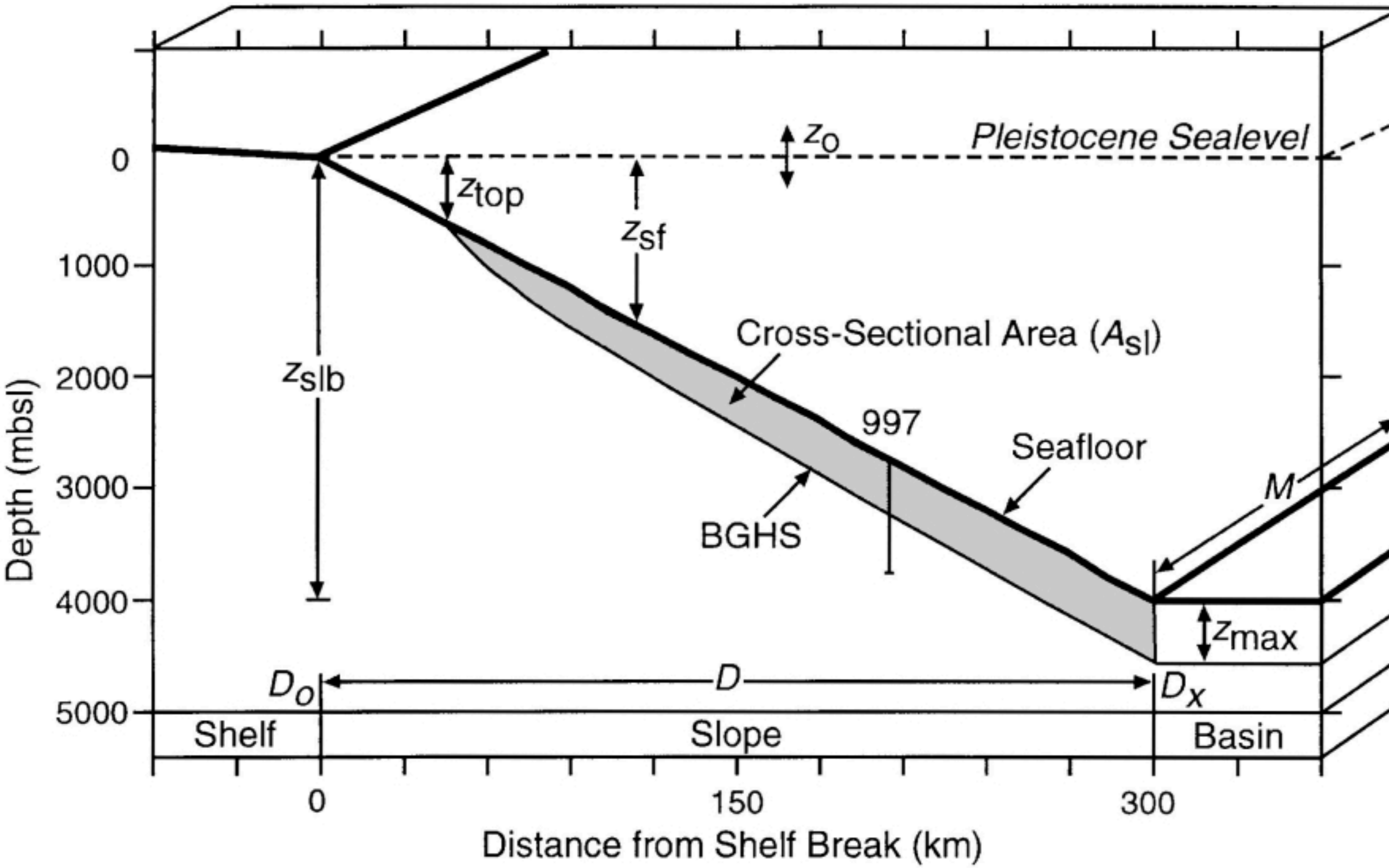
Bhatnager et al., Am. J. Sci., 2007

Pore Waters Above Gas Hydrate (Hydrate Ridge)



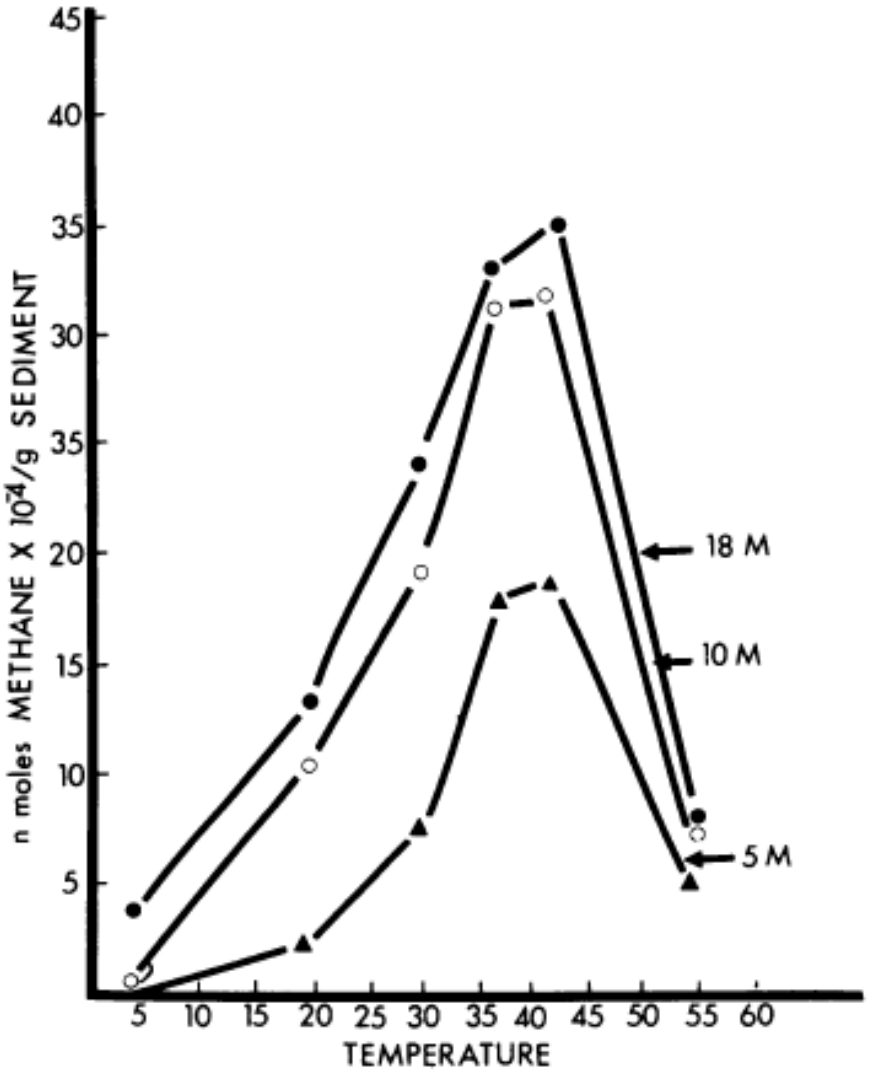
Chaterjee et al., JGR, 2011

Potential Volume of Gas Hydrate

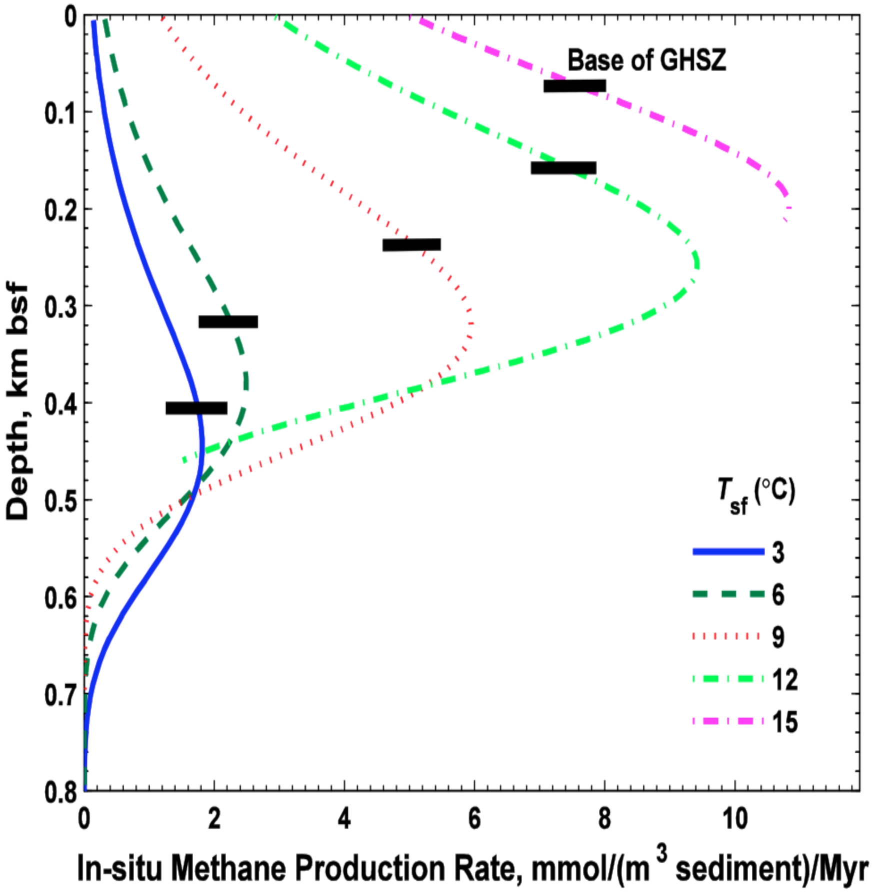


Dickens, Organic Geochemistry, 2001

Temperature Effect on Methanogenesis

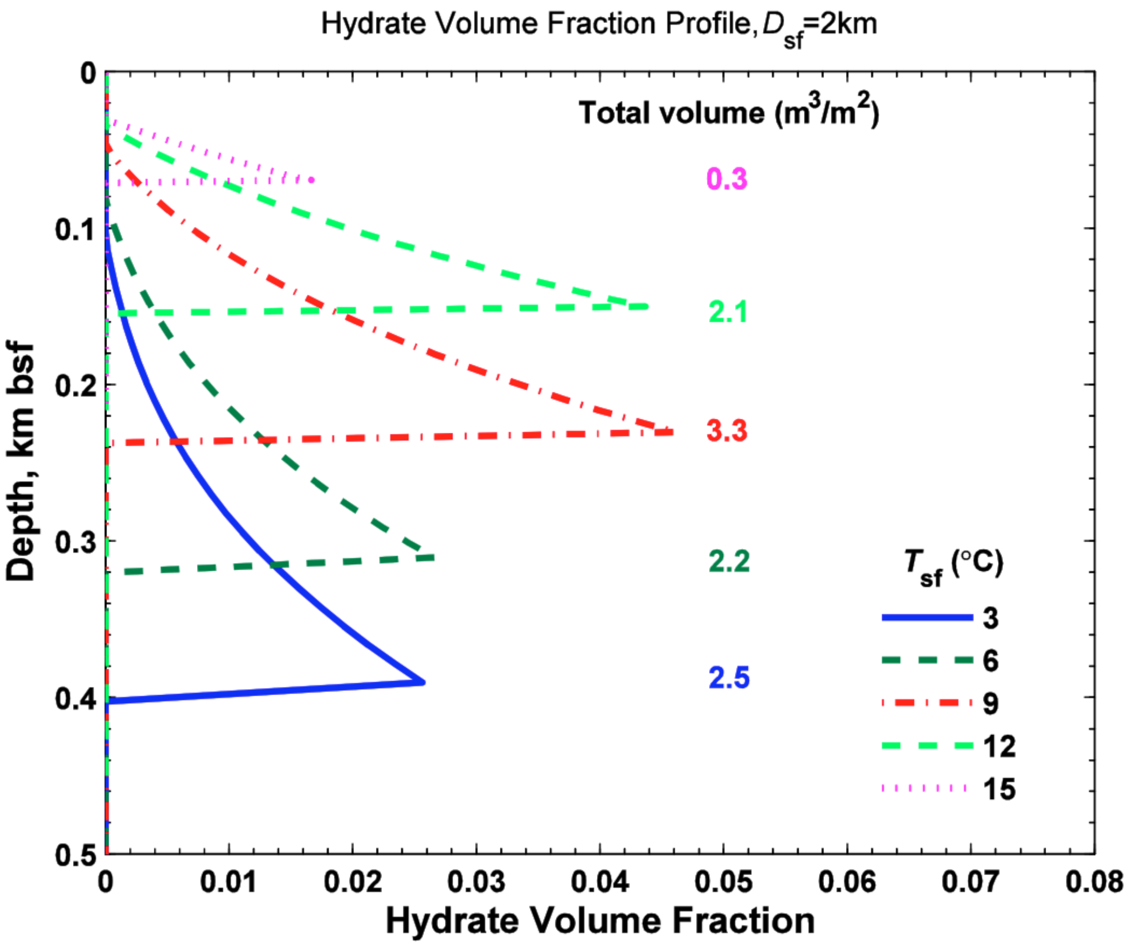


Zeikus & Winfrey, 1976



Temperature Effect on Methane Production

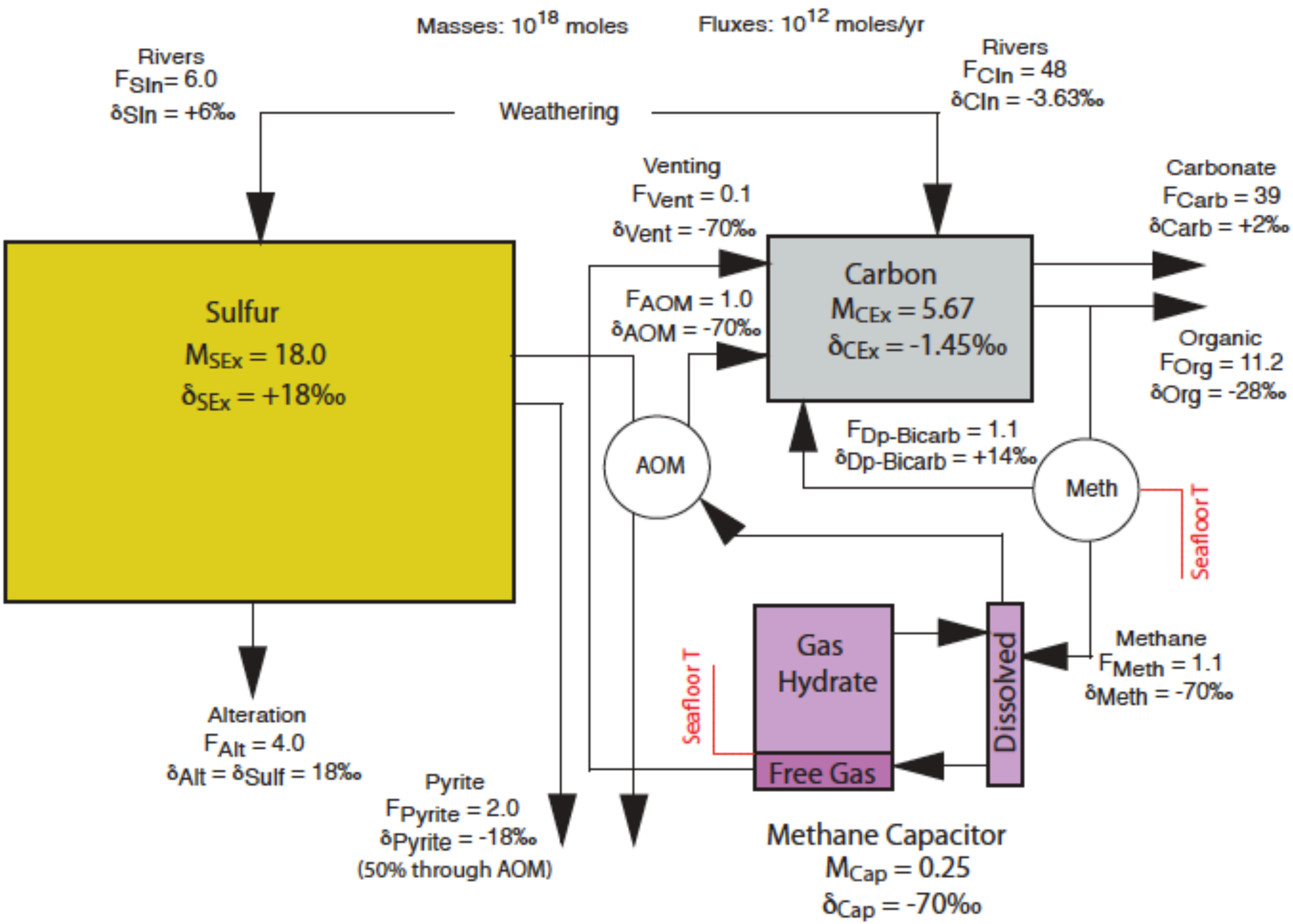
Gu, Dickens, Chaterjee et al. accepted



Temperature Effect on Gas Hydrate ***Distribution***

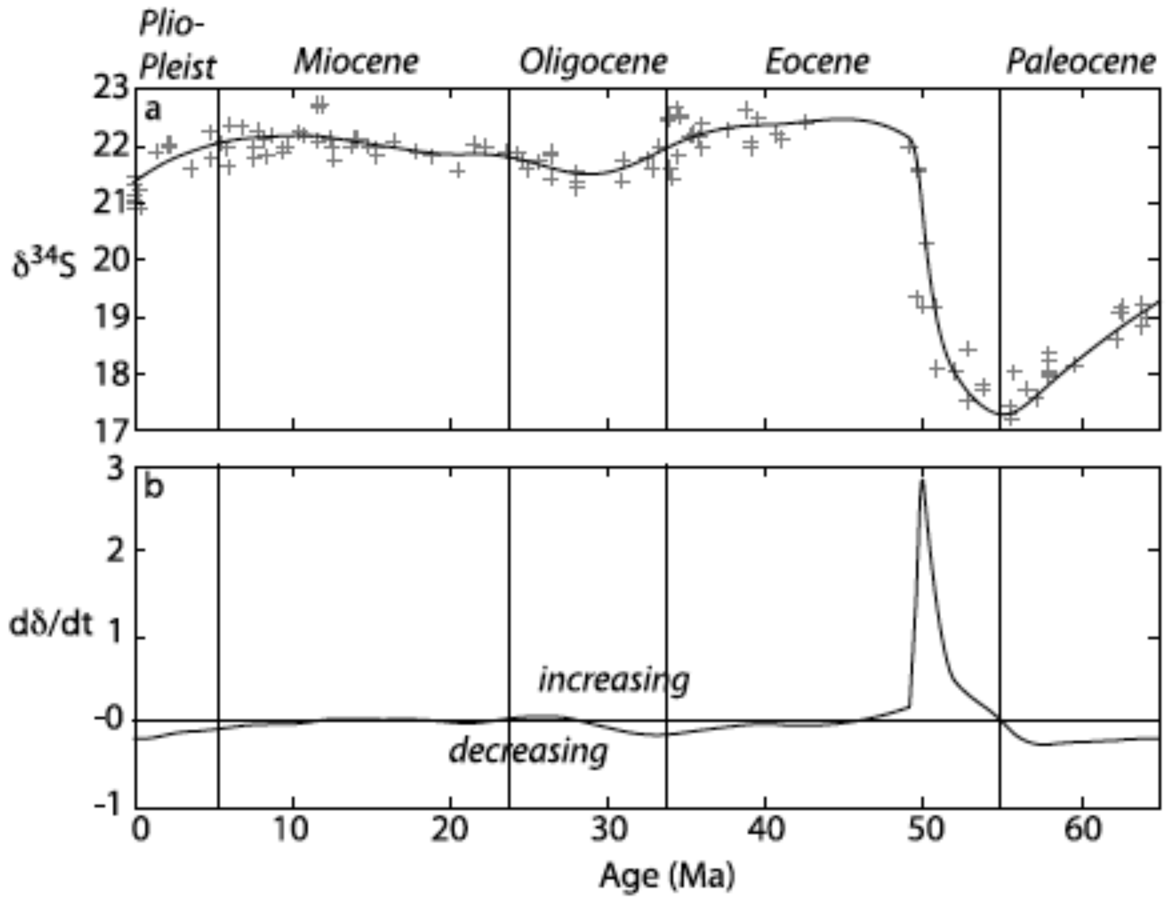
Gu, Dickens, Chaterjee et al. accepted

A Curious Machine

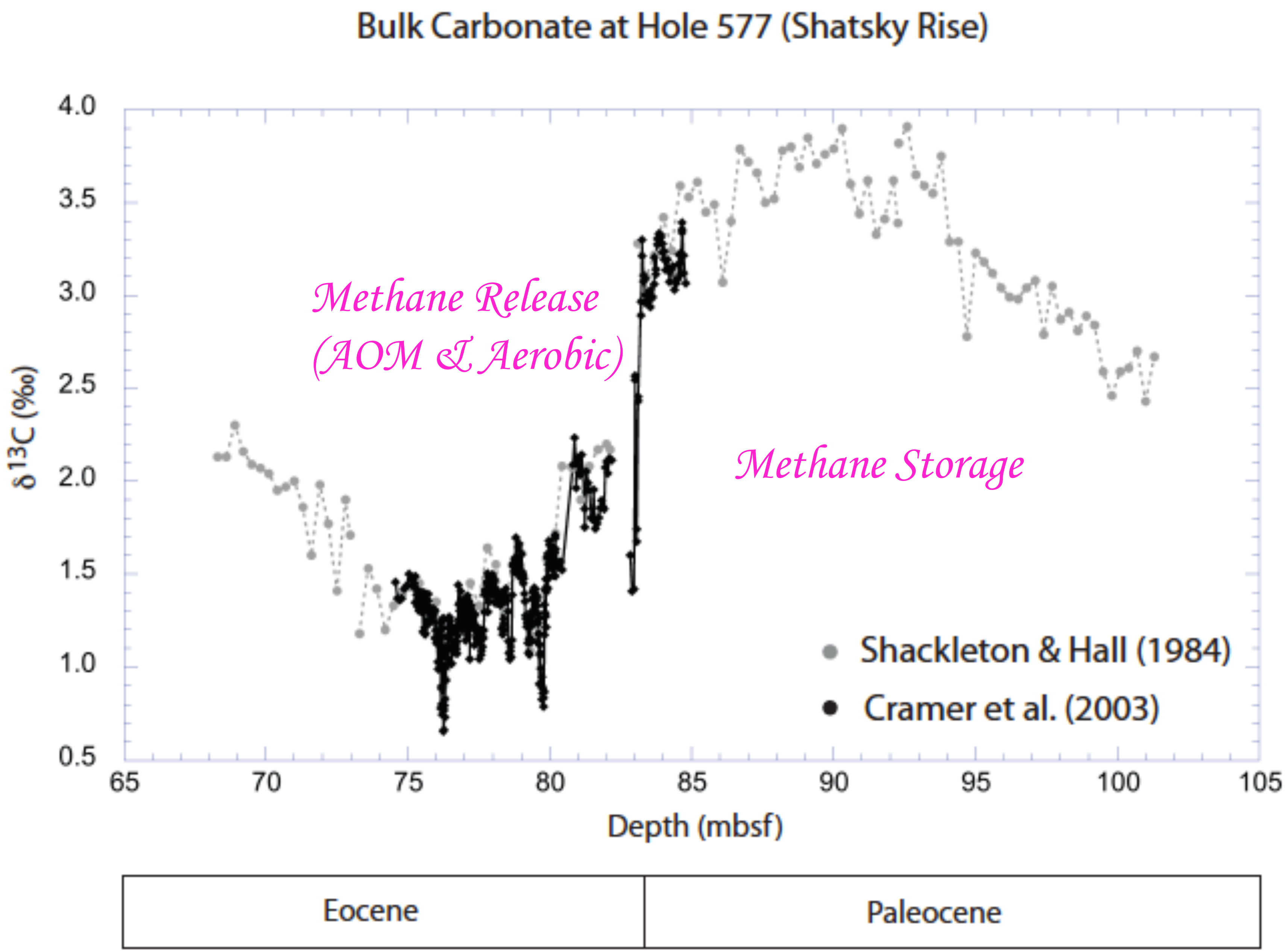


Dickens, COP, 2011

Fe Sulfides
= Enhanced AOM !

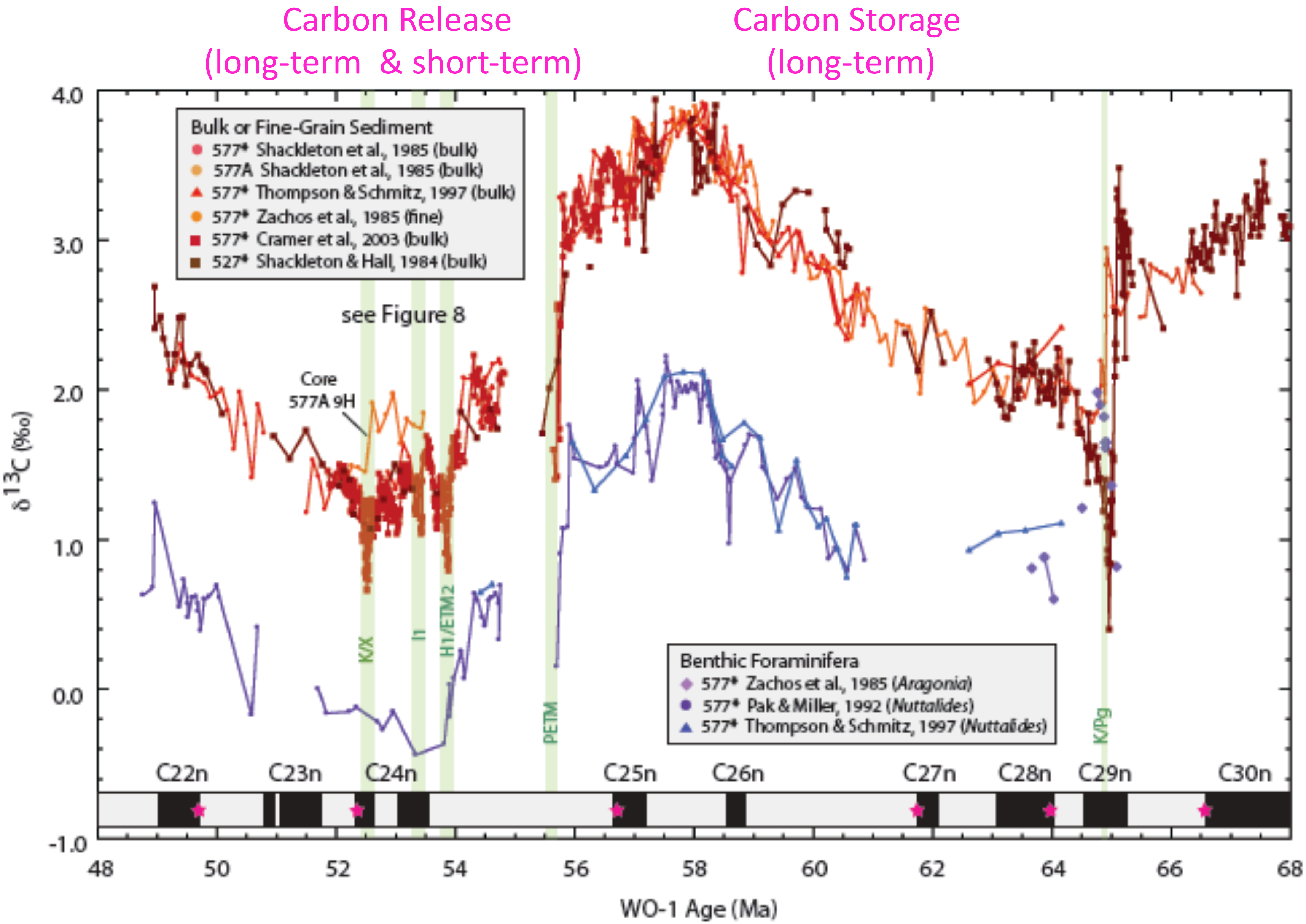


Kurtz et al., Paleoceanography, 2003



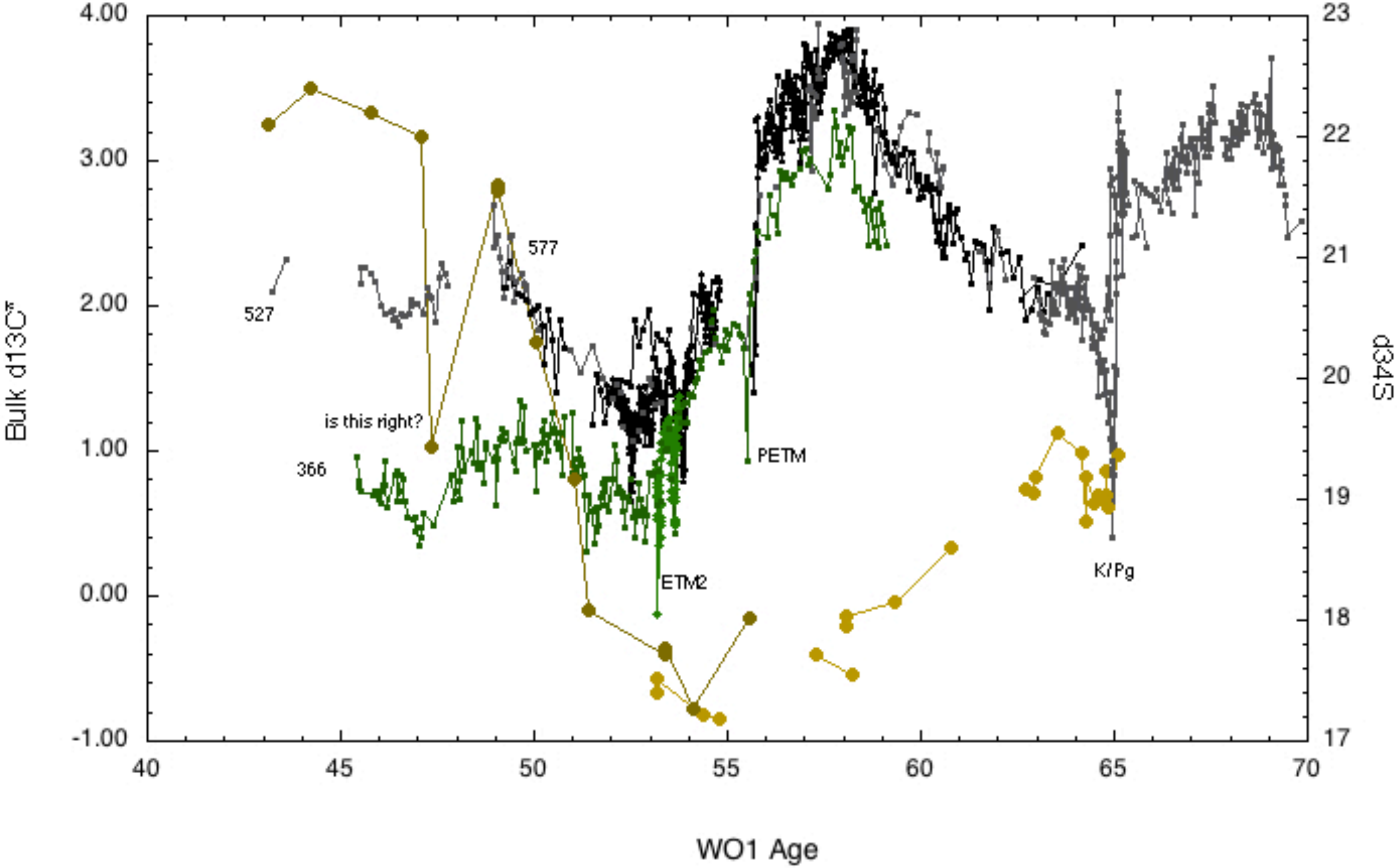
Bulk Carbonate at Hole 577 (Shatsky Rise)
δ 13C (‰)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
65
70
75
80
85
90
95
100
105
Depth (mbsf)
Methane Release
(AOM & Aerobic)
Methane Storage
Shackleton & Hall (1984)
Cramer et al. (2003)
Eocene
Paleocene

Carbon Isotope Records at DSDP Site 577



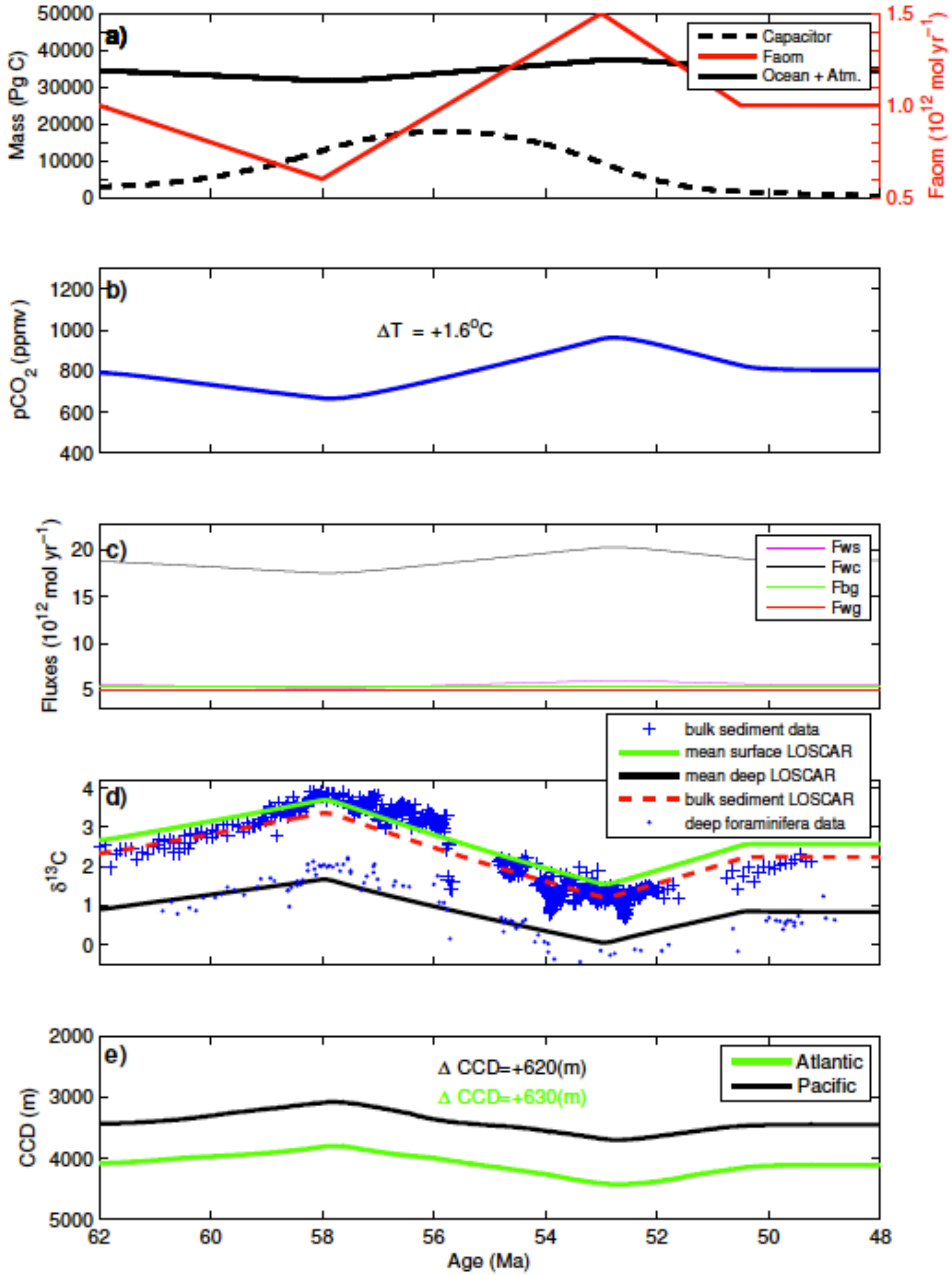
[*Dickens and Backman, News. Strat., 2013*]

Sulfur Isotopes (Correct Age)



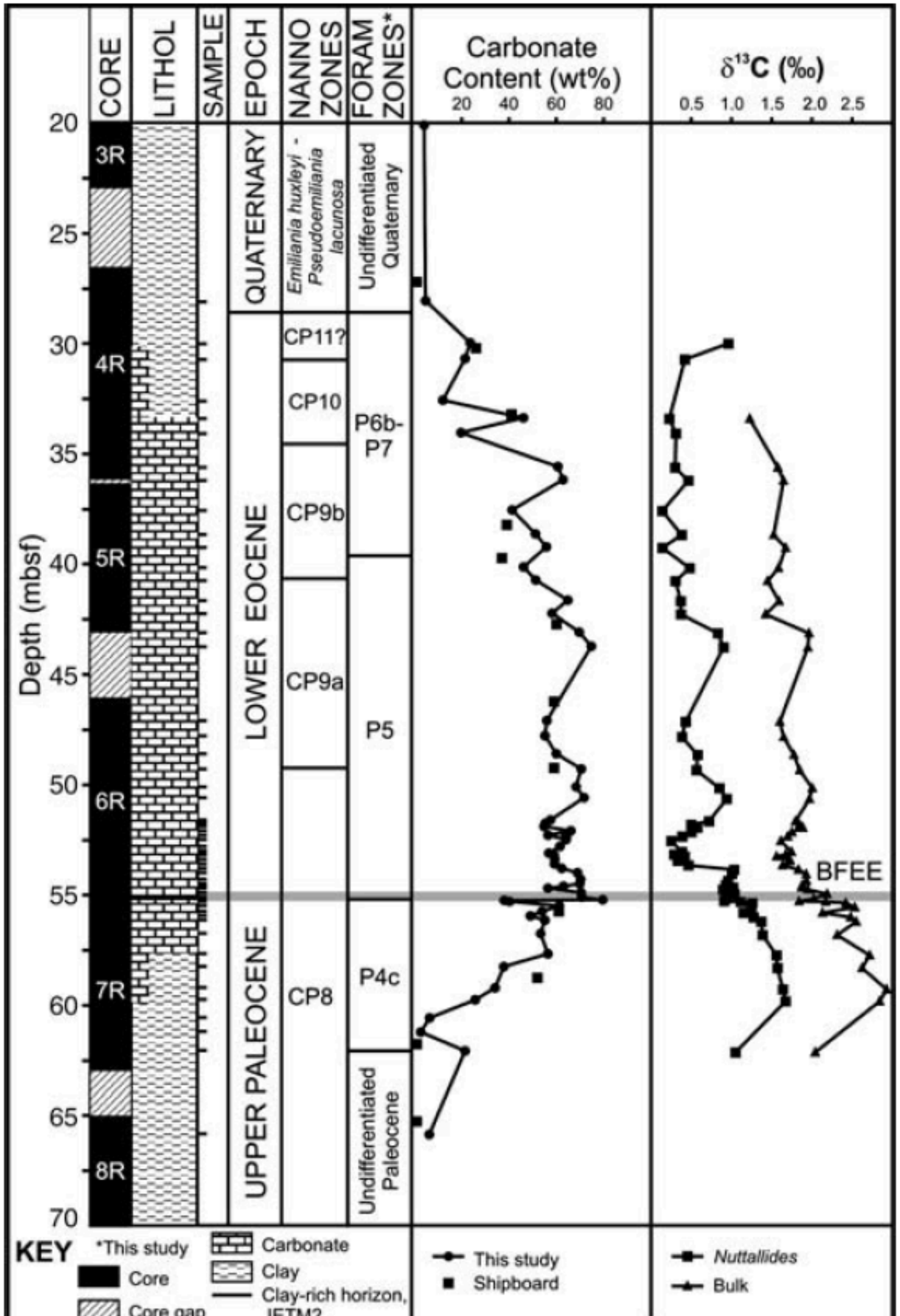
[original sulfur data from *Paytan et al.*, 1996]

Long-term Model Results



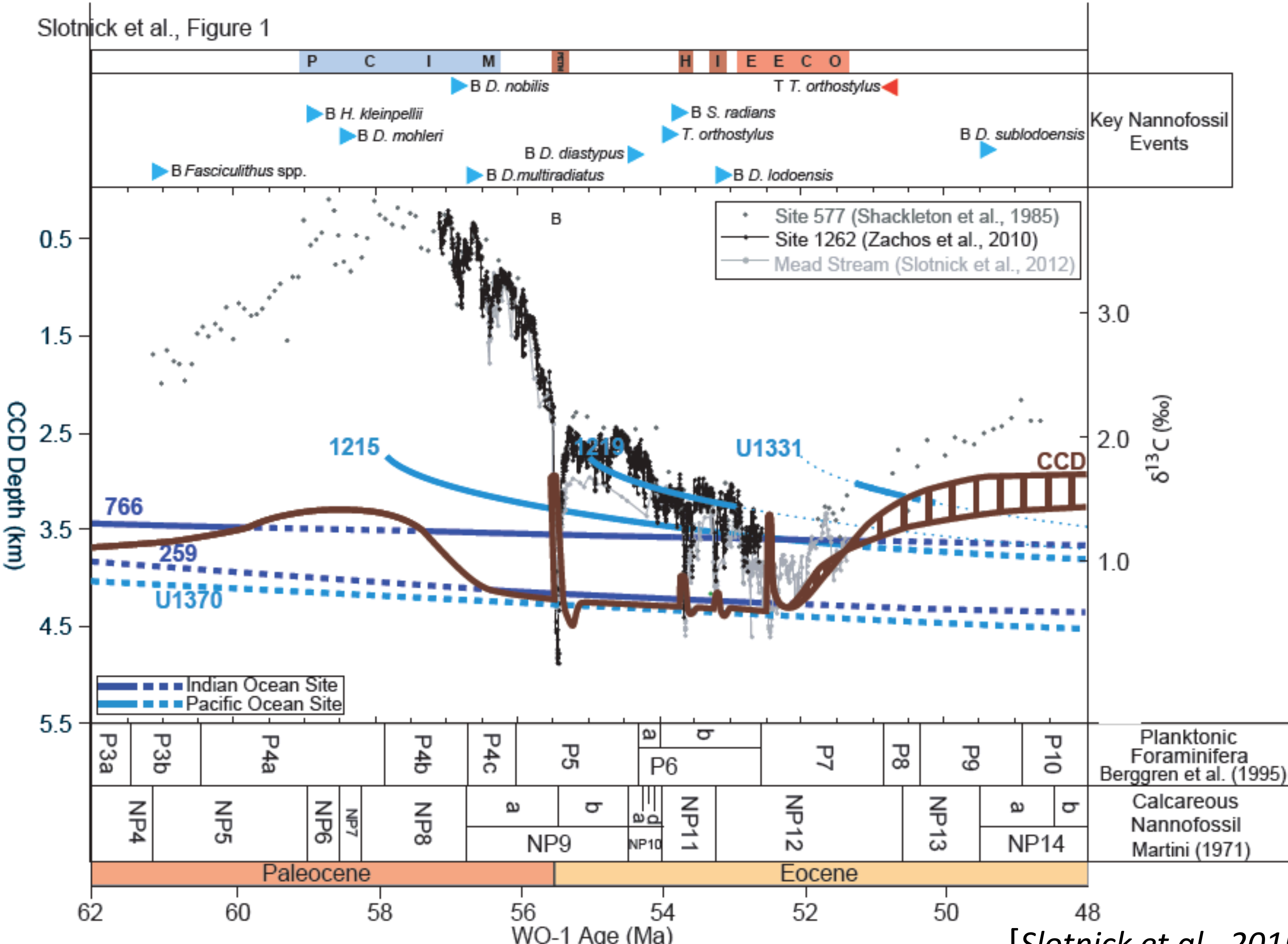
[*Komar et al.,*
Paleoceanography, 2013]

DSDP Site 259 (Indian Ocean)



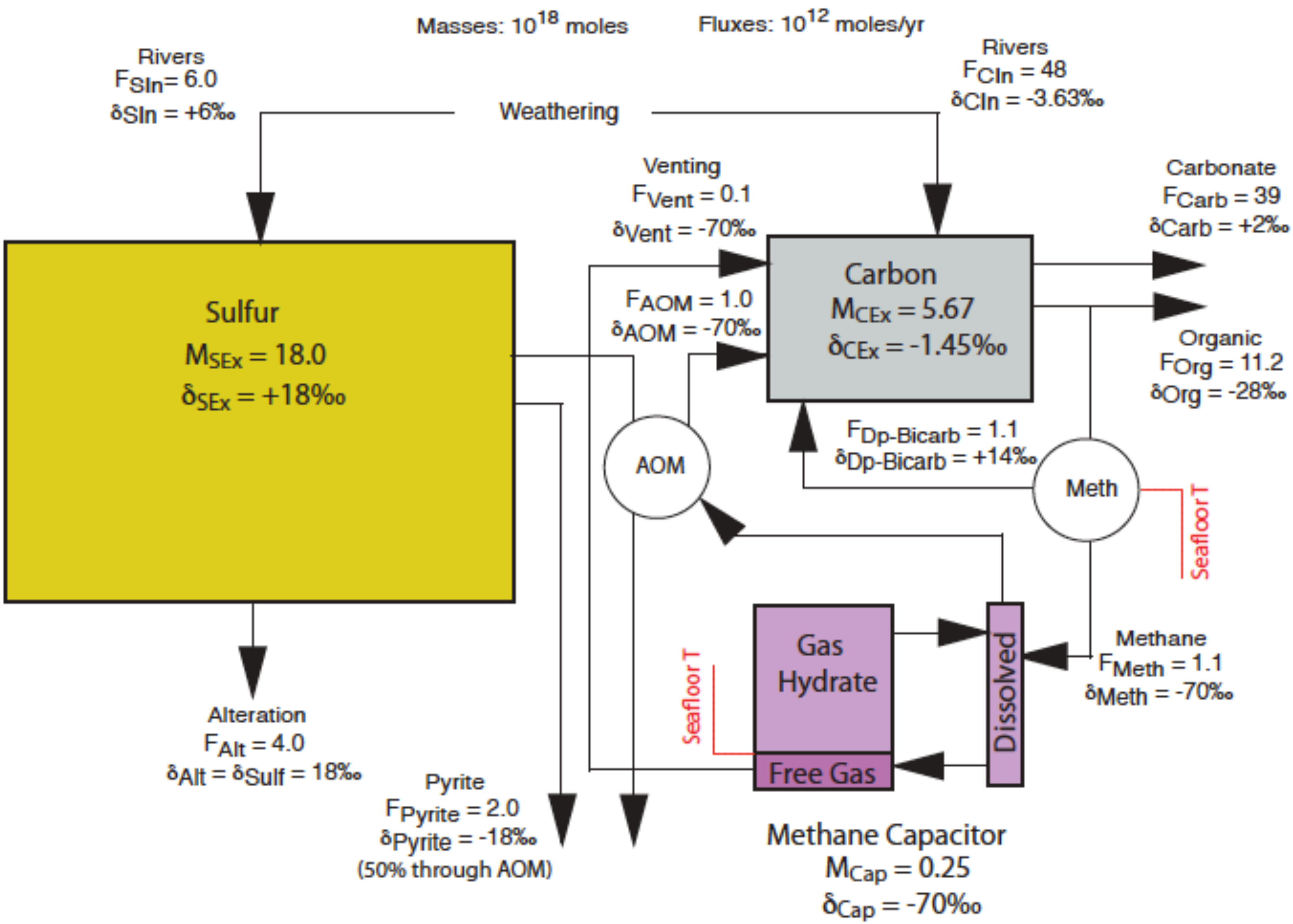
[*Hancock et al., IEJS, 2007*]

Indo-Pacific Paleogene CCD



[*Slotnick et al., 2015*]

A Curious Machine



Dickens, COP, 2011

14. Keeping Quaternary scientists at bay

Thank you